ENVIRONMENTAL FLOW STANDARDS IN WATER AVAILABILITY MODELING

A Thesis

by

CAMILO ANDRÉS CRISTANCHO

Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Chair of Committee,	Ralph Wurbs
Committee Members,	Anthony Cahill
	Clyde Munster
Head of Department,	Robin Autenrieth

August 2017

Major Subject: Civil Engineering

ABSTRACT

The Texas Commission on Environmental Quality (TCEQ) has established environmental flow standards in seven river systems through a process defined by the Texas Legislature in its 2007 Senate Bill 3 (SB3). The environmental flow standards have been incorporated in the state's water right permitting system with a priority date that corresponds to the date when the flow recommendations were received by the TCEQ. Therefore, all the environmental flow standards in the different systems are junior to the water rights previously granted in the state. This thesis first presents a comprehensive literature review of environmental flow standards and an explanation of the process that led to the implementation of environmental flow standards in Texas. Moreover, a comparative assessment regarding the structure of the environmental flow standards is presented to reveal the differences between the river systems defined by TCEQ.

Additionally, this thesis presents a research study that used frequency analyses and Water Rights Analysis Package capabilities to evaluate the attainment of environmental flow standards and the impacts of the standards on unappropriated flows. This assessment revealed that none of the standards are met 100% of the time due to the priority system that regulates surface water in the state. This system protects old water rights in the state, so environmental flow standards only affect water availability of future water rights. Because of this, this study included frequency analyses for unappropriated flows considering two scenarios for each system: (a) without including

SB3 standards and (b) including SB3 standards. These analyses revealed that attainment of environmental flow and water availability depends on the geographical location.

ACKNOWLEDGEMENTS

I would like to thank my committee chair, Dr. Wurbs, and my committee members, Dr. Cahill and Dr. Munster, for their guidance and support in the courses they taught me and in general throughout the course of this research. I want to especially thank Dr. Hoffpauir for his help in understanding the modeling process of pulse flows.

Thanks also go to my friends and colleagues and the department faculty and staff for making my time at Texas A&M University a great experience.

Moreover, the support of the TCEQ is gratefully acknowledged. However, the information presented in this academic thesis has not been validated by the TCEQ and does not necessarily represent the views or policies of the TCEQ. All errors or misrepresentations found in the thesis are the responsibility of the author, not the sponsor.

Finally, thanks to my mother, father, and sister for their encouragement and support.

CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supervised by a thesis committee consisting of Dr. Ralph Wurbs (committee chair) and Dr. Anthony Cahill of the Department of Civil Engineering and Dr. Clyde Munster of the Department of Biological and Agriculture Engineering.

Funding Sources

Graduate study was supported by a research assistantship funded by the TCEQ.

NOMENCLATURE

BBASC	Basin and Bay Area Stakeholders Committee
BBEST	Basin and Bay Expert Science Team
BRA	Brazos River Authority
DHI	Danish Hydraulics Institute
DO	Daily Target and Supplemental Options in WRAP
DW	Daily (Sub-Monthly) Water Right Input Data in WRAP
EF	Environmental Flow
FDC	Flow Duration Curve
FS	Flow Switch Record in WRAP
GSA	Guadalupe–San Antonio
IBWC	International Boundary and Water Commission
IF	Instream Flow Record in WRAP
IHA	Indicators of Hydrologic Alteration
NRC	National Research Council
PF	Pulse Flow Record in WRAP
PO	Pulse Flow Supplemental Options in WRAP
SB1	Senate Bill 1 enacted by the Texas Legislature in 1997
SB2	Senate Bill 2 enacted by the Texas Legislature in 2001
SB3	Senate Bill 3 enacted by the Texas Legislature in 2007
TCEQ	Texas Commission on Environmental Quality

TIFP	Texas Instream Flow Program
TO	Target Options Record in WRAP
TS	Target Series Record in WRAP
TWDB	Texas Water Development Board
USACE	United States Army Corps of Engineers
USBR	United States Bureau of Reclamation
USGS	United States Geological survey
WAM	Water Availability Model
WR	Water Right Record in WRAP
WRAP	Water Rights Analysis Package

TABLE OF CONTENTS

Page

ABSTRACT ii

ACKNOWLEDGEMENTS iv

CONTRIBUTORS AND FUNDING SOURCES...v

NOMENCLATURE...vi

LIST OF FIGURES...x

LIST OF TABLES xi

1. INTRODUCTION AND LITERATURE REVIEW...1

1.1 Background 1
1.2 Literature Review 2
1.2.1 Environmental Flow 2
1.2.2 Generalized Modeling Systems in Water Resources 8
1.2.3 Metrics to Assess Environmental Flows 12
1.2.4 Statistical Frequency Analysis to Assess Environmental Flow Standards 14
1.3 Research Objectives 16

2. SB3 ENVIRONMENTAL FLOW STANDARDS 18

2.1 Environmental Flow in Texas 18
2.2 SB3 Process for Establishing Environmental Flow Standards.............................19
2.3 SB3 Environmental Flow Standards for the Individual River Systems 20
2.3.1 Trinity and San Jacinto Rivers and Galveston Bay..20
2.3.2 Sabine and Neches Rivers and Sabine Lake 21
2.3.3 Colorado and Lavaca Rivers and Matagorda and Lavaca Bays.........................22
2.3.4 Guadalupe, San Antonio, Mission, and Aransas Rivers and Mission, Copano, Aransas, and San Antonio Bays..25
2.3.5 Nueces River and Corpus Christi and Baffin Bays 26
2.3.6 Brazos River and Its Associated Bay and Estuary System 28
2.3.7 Rio Grande, Rio Grande Estuary, and Lower Laguna Madre 30
2.4 Comparative Evaluation of the Structure and Metrics Adopted for the Standards 31

2.4.1 Definition of Seasons 32
2.4.2 Use of Hydrologic Condition and Hydrologic Index 33
2.4.3 Hydrologic Condition Index 34
2.4.4 Control Points 35

3. WATER AVAILABILITY MODELING SYSTEM 37

3.1 WAM/WRAP Modeling System 37
3.2 Daily Water Availability Models for the Selected River Systems 40
3.2.1 Trinity and San Jacinto Rivers and Galveston Bay 41
3.2.2 Sabine and Neches Rivers and Sabine Lake 43
3.2.3 Colorado and Lavaca Rivers and Matagorda and Lavaca Bays 45
3.2.4 Guadalupe, San Antonio, Mission, and Aransas Rivers and Mission, Copano, Aransas, and San Antonio Bays 47
3.2.5 Brazos River and Its Associated Bay and Estuary System 48
3.3 Modeling SB3 Environmental Flow Standards in the WRAP/WAM System 50
3.3.1 Modeling SB3 Flow Standards in Daily Simulation 50
3.3.2 Converting Simulated Daily Targets to Monthly Targets 53
3.3.3 Proposed Modeling Approach Example 55

4. ATTAINMENT OF ENVIRONMENTAL FLOW STANDARDS 59

5. TARGETS FROM DAILY SIMULATIONS INTO MONTHLY MODELS 81

6. IMPACT OF ENVIRONMENTAL FLOW STANDARDS ON WATER AVAILABILITY 90

7. SUMMARY AND CONCLUSIONS 110

REFERENCES 115

LIST OF FIGURES

Page

Figure 1 Major River Basins Defined by the TWDB..41

Figure 2 Trinity River System (Wurbs, 2017f)..42

Figure 3 Sabine River System (Wurbs, 2017c)..44

Figure 4 Neches River System (Wurbs, 2017b)..45

Figure 5 Colorado River System (Wurbs, 2017e)..46

Figure 6 GSA Rivers System (Wurbs, 2017a)..47

Figure 7 Brazos River System (Wurbs, 2017d)..49

Figure 8 SIMD Input Records for Subsistence and Base Flow Standards at West Fork Trinity River near Grand Prairie..52

Figure 9 SIMD Input Records for Pulse Flow Standards at West Fork Trinity River near Grand Prairie..53

Figure 10 HYD Input File for Creating TS Records..55

Figure 11 SIM Input Modification in the IF Record to Include TSF File.......................55

Figure 12 SIM Input TIN File..56

Figure 13 Instream Target Series at Control Point Hemp (acre-feet).............................57

Figure 14 Percentage of Time Without Instream Flow Shortages and Drainage Area at EF Control Points..80

Figure 15 Schematic of Trinity System (Wurbs, 2017f)...104

Figure 16 Schematic of Sabine System (Wurbs, 2017c)...105

Figure 17 Schematic of Neches System (Wurbs, 2017b)...106

Figure 18 Schematic of GSA System (Wurbs, 2017a)...107

Figure 19 Schematic of Colorado System (Wurbs, 2017e)...108

Figure 20 Schematic of Brazos System (Wurbs, 2017d)...109

LIST OF TABLES

Page

Table 1 Attainment Metrics for Environmental Flow Standards 15

Table 2 Gaging Stations in Trinity-San Jacinto System 21

Table 3 Gaging Stations in the Sabine System 22

Table 4 Gaging Stations in the Colorado-Lavaca System...23

Table 5 Gaging Stations in the GSA System 25

Table 6 Gaging Stations in the Nueces-Corpus System..27

Table 7 Gaging Stations in the Brazos System 29

Table 8 Gaging Stations in the Rio Grande System..30

Table 9 Seasons Defined for Each System...32

Table 10 Systems Affected by Hydrologic Condition 33

Table 11 Frequency Probability to Determine Hydrologic Condition............................34

Table 12 Hydrologic Index by River Basin..35

Table 13 Number of Control Points at Each System 36

Table 14 Environmental Flow Standards at West Fork Trinity River near Grand Prairie, Trinity River System...51

Table 15 Instream Flow Shortages (acre-feet/month)...58

Table 16 Control Point Names and Identifier in Trinity WAM......................................60

Table 17 Control Point Names and Identifier in Sabine WAM......................................60

Table 18 Control Point Names and Identifier in the Sabine WAM 60

Table 20 Control Point Names and Identifier in GSA WAM...61

Table 21 Control Point Names and Identifier in Brazos WAM......................................62

Table 22 Frequency Metrics for Monthly Summations of Daily Instream Flow Shortage Volumes at SB3 EF Sites in the Trinity River System (acre-feet/month)....66

Table 23 Frequency Metrics for Monthly Summations of Daily Instream Flow Shortage Volumes at SB3 EF Sites in the Sabine River System (acre-feet/month)....66

Table 24 Frequency Metrics for Monthly Summations of Daily Instream Flow Shortage Volumes at SB3 EF Sites in the Neches River System (acre-feet/month)....66

Table 25 Frequency Metrics for Monthly Summations of Daily Instream Flow Shortage Volumes at SB3 EF Sites in the Colorado River System (acre-feet/month)....67

Table 26 Frequency Metrics for Monthly Summations of Daily Instream Flow Shortage Volumes at SB3 EF Sites in the GSA River System (acre-feet/month)....68

Table 27 Frequency Metrics for Monthly Summations of Daily Instream Flow Shortage Volumes at SB3 EF Sites in the Brazos River System (acre-feet/month)....68

Table 28 Frequency Metrics for Daily Instream Flow Shortage Volumes at SB3 EF Sites in the Trinity River System....69

Table 29 Frequency Metrics for Daily Instream Flow Shortage Volumes at SB3 EF Sites in the Sabine River System (acre-feet/day)....69

Table 30 Frequency Metrics for Daily Instream Flow Shortage Volumes at SB3 EF Sites in the Neches River System (acre-feet/day)....69

Table 31 Frequency Metrics for Daily Instream Flow Shortage Volumes at SB3 EF Sites in the Colorado River System (acre-feet/day)....70

Table 32 Frequency Metrics for Daily Instream Flow Shortage Volumes at SB3 EF Sites in the GSA River System (acre-feet/day)....70

Table 33 Frequency Metrics for Daily Instream Flow Shortage Volumes at SB3 EF Sites in the Brazos River System (acre-feet/day)....71

Table 34 Percentage of Time with a Non-Zero Instream Flow Shortage in Each System....71

Table 35 Pulse Flow Summary for the Trinity River System 73

Table 36 Pulse Flow Summary for the Sabine River System 73

Table 37 Pulse Flow Summary for the Neches River System 74

Table 38 Small Pulse Flow Summary for the Colorado River System 74

Table 39 Large Pulse Flow Summary for the Colorado River System 75

Table 40 Annual Pulse Flow Summary for the Colorado River System..........................75

Table 41 Colorado River System Pulse Flow Summary (every 18 months) 76

Table 42 Colorado River System Pulse Flow Summary (every 2 years).........................76

Table 43 Small Pulse Flow Summary for the GSA System..77

Table 44 Large Pulse Flow Summary for the GSA System..77

Table 45 Periodic Pulse Flow Summary for GSA System..78

Table 46 Pulse Flow Summary for the Brazos System 79

Table 47 Attainments of Pulse Events in Each System 79

Table 48 Frequency Metrics for Monthly Instream Flow Shortage Volumes at SB3 EF Sites in the Trinity River System (acre-feet/month) 82

Table 49 Frequency Metrics for Monthly Instream Flow Shortage Volumes at SB3 EF Sites in the Sabine River System (acre-feet/month) 82

Table 50 Frequency Metrics for Monthly Instream Flow Shortage Volumes at SB3 EF Sites in the Neches River System (acre-feet/month) 83

Table 51 Comparison of Maximum Instream Flow Shortage Volumes at SB3 EF Sites (acre-feet/month)..84

Table 52 Percentage of Time with a Non-Zero Instream Flow Shortage in Each System..84

Table 53 Frequency Metrics for Monthly Regulated Flow Volumes at SB3 EF Sites in the Trinity River System (acre-feet/month)...86

Table 54 Frequency Metrics for Monthly Regulated Flow Volumes at SB3 EF Sites in the Sabine River System (acre-feet/month)...87

Table 55 Frequency Metrics for Monthly Regulated Flow Volumes at SB3 EF Sites in the Neches River System (acre-feet/month) 88

Table 56 Monthly Mean Regulated Flow Volumes Comparison at SB3 EF Sites (acre-feet/month) 89

Table 57 Frequency Metrics for Daily Unappropriated Flow Volumes at SB3 EF Sites in the Trinity System (acre-feet/day) 92

Table 58 Frequency Metrics for Daily Unappropriated Flow Volumes at SB3 EF Sites in the Sabine System (acre-feet/day) 93

Table 59 Frequency Metrics for Daily Unappropriated Flow Volumes at SB3 EF Sites in the Neches System (acre-feet/day) 94

Table 60 Frequency Metrics for Daily Unappropriated Flow Volumes at SB3 EF Sites in the GSA System (acre-feet/day) 95

Table 61 Frequency Metrics for Daily Unappropriated Flow Volumes at SB3 EF Sites in the GSA System (acre-feet/day) 96

Table 62 Frequency Metrics for Daily Unappropriated Flow Volumes at SB3 EF Sites in the GSA System (acre-feet/day) 97

Table 63 Frequency Metrics for Daily Unappropriated Flow Volumes at SB3 EF Sites in the Colorado System (acre-feet/day) 98

Table 64 Frequency Metrics for Daily Unappropriated Flow Volumes at SB3 EF Sites in the Colorado System (acre-feet/day) 98

Table 65 Frequency Metrics for Daily Unappropriated Flow Volumes at SB3 EF Sites in the Colorado System (acre-feet/day) 99

Table 66 Frequency Metrics for Daily Unappropriated Flow Volumes at SB3 EF Sites in the Brazos System (acre-feet/day) 99

Table 67 Frequency Metrics for Daily Unappropriated Flow Volumes at SB3 EF Sites in the Brazos System (acre-feet/day) 100

Table 68 Frequency Metrics for Daily Unappropriated Flow Volumes at SB3 EF Sites in the Brazos System (acre-feet/day) 101

Table 69 Frequency Metrics for Daily Unappropriated Flow Volumes at SB3 EF Sites in the Brazos System (acre-feet/day) 102

Table 70 Percentage of Time with Non-Zero Unappropriated Flows in Each System....103

1. INTRODUCTION AND LITERATURE REVIEW

1.1 Background

Providing reliable water supplies for population and economic growth while preserving the vitality of riverine ecosystems is important worldwide (Gippel, Cosier, Markarc, & Liud, 2009; O'Keefe, Raven, & Boon, 2012; Paredes-Arquiola, Martinez-Capel, Solera, & Aguilella, 2013). The scientific literature regarding flow characteristics necessary for healthy ecosystems is extensive (Acreman & Dunbar, 2004; Poff & Zimmerman, 2009). Protecting instream flows in the river systems of Texas has been a concern for many years. However, efforts in establishing expanded environmental flow standards have intensified pursuant to recent legislation (Wurbs, 2015a). The study reported in this thesis investigated recently created environmental flow standards in Texas and incorporation of the standards in water availability modeling. Assessments were performed on the capabilities for establishing and meeting environmental flow requirements and the impacts of the environmental flow requirements on capabilities for supplying municipal, industrial, agricultural, and other water uses.

Senate Bills 1, 2, and 3 enacted by the Texas Legislature in 1997, 2001, and 2007, respectively, provide the institutional setting for the thesis research. The Water Rights Adjudication Act of 1967 authorized creation of the present water rights permit system through a 25-year adjudication process consolidating an unmanageable array of diverse water rights that had evolved over several hundred years (Wurbs, 2004). The 1997 Senate Bill 1 (SB1) authorized creation of a water availability modeling (WAM) system to support the administration of the water rights permit system, other water allocation mechanisms, and regional and statewide planning (Wurbs, 2005). The 2001 Senate Bill 2 (SB2) created the Texas Instream Flow Program (TIFP) that includes comprehensive detailed studies for determining environmental flow needs throughout the state and establishing measures for preserving environmental flows. Recognizing that many more years will be required to complete the work being performed under the TIFP, the 2007 Senate Bill 3 (SB3) instigated a process for expediting establishment of environmental flow standards for selected priority river systems and incorporating these standards in the water rights permit system and associated WAM system (Wurbs, 2015b).

Environmental flows include freshwater inflows to bays and estuaries as well as flow in inland stream systems. Environmental flow requirements were initially defined in Texas, like elsewhere, as minimum flow limits. Nevertheless, in Texas, like elsewhere, the importance of considering all elements of a flow regime is now well recognized. SB3 environmental flow standards are defined based on flow regimes with subsistence, base, and high flow components that describe the magnitude, frequency, duration, and timing of flows required to maintain sound ecosystems.

1.2 Literature Review

1.2.1 Environmental Flow

The term *environmental flow* has evolved over the past decades, and it is also referred to as *instream flow* or *ecological flow*. This constant evolution can be seen in the following definitions, which correspond to the old and current understanding of instream flow.

In the old definition, instream flow is just a minimum amount of water that has to be flowing in a river to maintain a sound ecological environment, while competing with some water uses, such as irrigation, public supply, recreation, hydropower, and the like. However, the current approach considers that instream flows should be concerned about the maintenance of the ecosystem as a whole rather than just the river. Furthermore, the environmental flow should mimic, as close as possible, the natural regime of the river. The current understanding of instream flow is the product of the evolution of the following four trends:

1. From minimal flows to flow regimes.
2. From single-species to general ecosystem focus.
3. From simply a channel focus to focus on inclusion of the riparian and floodplain areas.
4. From standards developed solely based on hydrology to the implementation of a multidisciplinary approach.

In general, there are four environmental flow approaches: *look-up tables*, *desktop analysis*, *functional analysis*, and *hydraulic analysis* (Acreman & Dunbar, 2004). The complexity of each approach varies widely regarding the time required to gather all the input information to develop the final environmental flow. These methodologies are briefly explained in the following paragraphs.

The look-up tables' methodology provides a flow target based on the input parameters (hydrologic indices, river characteristics, etc.); therefore, it is considered the easiest approach to implement. The look-up tables are generally calibrated to specific regions, so to implement this method on a river that does not have look-up tables might be costly and time consuming to calibrate. Because of those issues and the fact that even after calibration the parameters might not fully represent the study area, this approach is normally reserved as an initial step to develop the final environmental flow.

The second method, desktop analysis, is characterized by the use of existing information, such as hydrologic flow records and ecological variables. This approach can be further subdivided into the (a) *hydrologic method* and (b) *hydrologic and ecologic method*. The latter is considered to be the most powerful because it considers both flow regime and ecological relationships, although when incorporating that method, it tends to be difficult to find all the required ecological information. On the other hand, hydrologic methods are statistical analyses of the flow records to replicate flow characteristics; therefore, the required information is normally provided by government entities.

The third methodology incorporates ecosystems, biological data, and hydrological and hydraulics analysis, and it is known as functional analysis. Due to the diverse number of factors considered by this approach, a lot of input information is required, and sometimes it can be difficult to obtain. However, if all the information is available, experts of physical and biological sciences can analyze the data to build flow regimes—through judgment calls made by the panel of experts—that are beneficial to the riverine ecosystem.

The last approach, hydraulic analysis, relates physical variables to specific conditions required by key species. The most commonly used physical variables are velocity, wetted perimeter, and depth. This approach uses 2D and 3D hydraulic modeling to determine the value of the physical variables; therefore, the precision of the thresholds provided by these variables change depending on the model.

Based on the information presented above, one can see that there is not a universal approach or methodology that can assure a perfect environmental flow. However, with current knowledge level, it is safe to conclude that the best results are obtained when groups of experts from several disciplines work together while considering the necessities of all the stakeholders in the riverine ecosystem.

The National Research Council (NRC, 2005) proposed the following principles that should be followed by the developers of new instream flow standards:

- Steps should be taken to preserve the whole function of the ecosystem rather than one species.
- The instream flow should resemble the natural flow regime, which implies the use of seasonal variability instead of a single minimum value for the whole year.
- Riparian corridor and flood plains should be included rather than just a focus on the main channel.
- The studies need to be done with an interdisciplinary approach that includes experts from academia and the public and private sectors. These experts come from different backgrounds.

- Adaptive management to adjust operational plans should be implemented in order to meet the objectives of the instream flow.
- Stakeholder's involvement in the development of instream flow should be ensured. Public contribution is vital to increasing the public support of any regulation such as an instream flow.

The process set up by the 1997 SB3 ensured that the final environmental flow standards established by the Texas Commission on Environmental Quality (TCEQ) are coherent with the principles mentioned before. Due to the broad spectrum covered by these principles, it can be concluded that the final environmental flow standards are the product of balancing technical and non-technical needs (National Research Council, 2005). The technical needs refer to findings and recommendations from all the studies produced by the experts, while the non-technical component is related to the legal, regulatory, and public implications that occur when certain instream flow standards are established. It is also important to underscore that the goals that are expected to be achieved by the implementation of an instream flow should be clear, cogent, and realistic in order to avoid misinterpretation of the results obtained.

As mentioned earlier, the final environmental flow standards established by the TCEQ follow the principles endorsed by the NRC; thus, the TCEQ implemented standards try to resemble the natural hydrology. Importantly, the general scheme of instream flow standards in Texas contains five components that are important to understand.

First, *subsistence flow* is defined as the minimum flow required to maintain tolerable water quality standards as well as to provide minimal conditions required for survival by both riparian and aquatic species. It is important to underscore that this flow only occurs during drought seasons and allows species to recolonize once base flow conditions return (Wurbs & Hoffpauir, 2013).

Second, *base flow*, also known as average or normal flow, occurs in between storm events. The main objective of this flow is to provide adequate habitat conditions and variability for the benefit of the ecosystem.

Third, *high flow pulses* correspond to flow pulses generated due to storm events; thus, the main characteristics of this flow are short duration, high magnitude, and the fact that they occur during and after storm events. Even though this flow is a product of storm events, high pulses are contained within the channel. Moreover, maintaining physical habitat features and longitudinal connectivity are the main objectives of high flow pulses.

Fourth, *seasonal variability* is considered a key factor, so the environmental flow standards have been designed to mimic the natural flow variability, which is highly influenced by the seasons (winter, spring, summer, and fall). Therefore, the flows associated with base and subsistence flows change depending upon the season. The durations change depending on the geographical location of the place where the environmental flow standard is established.

The last component, *hydrologic condition*, considers the fact that flow requirements change whether or not there is a drought period. During drought periods, the flows associated with subsistence and base flow standards are lower than the flow rates during wet periods. In order to determine the hydrologic condition, the TCEQ has established the use of cumulative flows, reservoir and lake levels, and the Palmer drought index to determine the presence of a drought period. These indicators are used at the beginning of each season.

In order to ensure the appropriate distribution of water among all the uses—hydroelectric generation, municipal and public supply, irrigation, storage, and instream flows—a modeling system has to be used. This modeling system has to deal with all the decision variables that interact within river/reservoir systems in order to determine how to adequately distribute water. The different types of modeling systems are described in the next section.

1.2.2 Generalized Modeling Systems in Water Resources

Environmental flows are usually modeled within generalized modeling systems that allow the user to not only assess instream requirements but also consider their effects on the river/reservoir system of interest. The main characteristics of this type of model are that it can be used in any location (Wurbs, 2011). This kind of modeling system is designed to deal with a broad range of problems or situations. Because of this flexibility, generalized models tend to be key tools to support decision-making situations.

Due to the importance of water to our society, several generalized models have been created to either describe a system or make decisions regarding a system under certain conditions, also known as parameters. The following is a brief compilation of the most broadly used models.

HEC-ResSim was developed by the United States Army Corps of Engineers (USACE), and its main objective is to simulate reservoir operations at one or more reservoirs by considering all the possible goals and constraints. It can perform simulations with time steps ranging from 15 minutes to 1 day (Klipsch & Hurst, 2013). Moreover, several routing methods are available for the user, and in general, it uses an upstream to downstream order to perform reservoir operations such as water supply, diversions, and hydropower.

MODSIM was developed at Colorado State University in order to support decision-making regarding long-, medium-, and short-term operations in a river/reservoir system. The simulations are performed using an objective function to assign priorities to different objectives. The simulation steps through time, and daily, weekly, or monthly time steps can be used (Labadie, 2006). This system uses network flow programming to solve the objective function. Additionally, instream flow can be modeled as a flow through-through demand within the network under analysis.

Hydrologics Inc. created OASIS, a model that uses a linear programming in which different goals and constraints can be assigned to nodes and arcs that conform the system. The program has great flexibility, allowing the user to select any time step between 5 minutes and 1 year (Hydrologics, Inc, 2009). Instream flow can be modeled as a minimum flow requirement in an arc.

The Center for Advanced Decision Support for Water and Environmental Systems developed RiverWare to support decision-making in a broad range of areas related to water resources. This software is promoted as highly flexible compared to other programs available due to the fact that it can be used to perform descriptive as well prescriptive simulations.

Water quality, hydropower generation, water rights, and hydrologic processes, among other interactions that occur within a river system, can be modeled with RiverWare (University of Colorado at Boulder, 2016). The user can perform simulations with computational time steps from 1 hour to 1 year. Because of this, RiverWare is extensively used in the western United States for official water rights concerns.

The Danish Hydraulics Institute (DHI) developed MIKE HYDRO BASIN for water resources analysis, planning, and management. This model can use daily or monthly time steps in addition to being able to run under GIS interface, which is an advantage since it is possible to use many features of GIS, one of which is catchment delineation. The versatility of the model allows it to be applicable to any river basin regardless of size or complexity. Furthermore, this model simulates the system as a network of nodes and arcs and is characterized by the DHI as a conceptual, distributive, and deterministic modeling system.

The California Department of Water Resources and the USBR developed CALSIM in an effort to simulate water resource systems for planning studies (Texas A&M and U.S. Bureau of Reclamation, 2007). The model uses linear programming to solve the objective function, whose parameters are defined by the user to distribute water on a network of nodes and arcs. Because of this, instream flows can be simulated as minimum flow targets in an arc. It is valid to underscore that CALSIM is not a prescriptive model, even though it utilizes optimization techniques at each time step.

Finally, the Water Rights Analysis Package (WRAP), developed at Texas A&M University, has been continuously expanding thanks to the statewide implementation of the Water Availability Model (WAM) system in Texas. WRAP simulates water resources management from a priority-driven point of view instead of performing computation from upstream to downstream as many other modeling systems do. It is valid to underscore that in the state of Texas, WRAP uses WAM as the input database; however, the program can be used to simulate any river basin once the input file has been generated.

The continuous endeavors by the TCEQ, consulting firms, and research community have led to the current version of WRAP that allows users to perform descriptive simulations with several time steps (daily, monthly, or other).The computational approach used in WRAP lets the user assign relative priorities to simulate several river system processes, such as hydropower generation, instream flow, reservoir release, river diversion, storage target, and more (Wurbs, 2011). Flow forecasting, routing, salinity simulation, and reservoir operation are also available in WRAP.

In general, it can be said that generalized modeling systems were developed to support decision-making when there are multiple variables present in the normal operation of river/reservoir system. Depending on the size of the system, the number of variables involved in the decision-making process can be large enough that is impossible to describe the behavior of the system without the use of generalized modeling system. Consequently, it is cogent to conclude that on river systems around the world, some kind of modeling system is being applied in order to manage water resources.

1.2.3 Metrics to Assess Environmental Flows

Several metrics and statistical analysis methods have been developed over the years to try to understand flow characteristics such as quantity and timing. Numerous endeavors to measure and analyze flow characteristics have been performed by various investigators. Researchers at Texas A&M University have focused on expanding capabilities for incorporating environmental flow requirements in the TCEQ WAM system (Wurbs & Hoffpauir, 2013; Pauls, 2014; Pauls & Wurbs, 2016); some of the developments consist of a set of 28 attainment metrics for assessing capabilities for satisfying environmental flow standards. In addition, the Nature Conservancy (2009) developed the software package Indicators of Hydrologic Alteration (IHA) to both create and analyze environmental flow standards. The following paragraphs further explain the content of the reports mentioned above.

The report entitled *Environmental Flows in Water Availability Model* (Wurbs & Hoffpauir, 2013) presents detailed examples of how to model SB3 environmental flow standards established by the TCEQ using the recently developed and expanded WRAP/WAM capabilities. This report explains how to obtain frequency statistics and other relevant information in order to measure the likelihood of attaining environmental flow standards.

The analysis presented by Wurbs and Hoffpauir (2013) used the Brazos River Basin and San Jacinto-Brazos Coastal Basin, called the Brazos WAM, as a case study to model and evaluate environmental flow requirements. The report focuses on a daily modeling time step but underscores the importance of the monthly modeling capabilities. This document is quite relevant not only because of the level of detail used to explain environmental flows modeling in the WRAP/WAM system, but also because all the expansions added to WRAP were tested with the Brazos WAM; therefore, the report set a precedent that explains how to incorporate TCEQ standards in the other WAMs systems available in the state of Texas.

Following the continuous improvement of WRAP capabilities, a total of 28 metrics (six for pulse events and 22 for any type of flow), were developed using Excel spreadsheets and WRAP daily simulation (SIMD) outputs (Pauls, 2014). This research used the Colorado and Trinity River systems as case studies to understand the attainment of several flow regimes at 18 control points. The research provided a range of results that led Pauls (2014) to conclude that WRAP offers the flexibility required to model complex flow standards, such as those present in the Colorado River, while using the recently added daily time step.

The results obtained with the 28 metrics showed significant differences in the attainment level of the environmental flow standards from one system to another. Therefore, it is possible to perceive the evolution or refinement process that occurred while defining the standards for the whole state of Texas.

As mentioned before, the Nature Conservancy developed the IHA as an easy-to-use tool that allows users to summarize and handle large data sets (Mathews & Richter, 2007). The IHA uses daily data for its calculations, and the reliability of the results depends on the assumptions made by the user and the length of the hydrologic record. This software is relevant due to the flexibility it offers and the fact that it uses a daily time step; the WRAP simulation outputs obtained with SIMD can be easily analyzed with the IHA.

This software can be used to created environmental flows or keep track of them thanks to its statistical capabilities and graphical editor tools. The IHA can be used to determine the percentage of time that a certain discharge is being met at a specific control point; it is possible to elaborate flow duration curve (FDC), which can help to understand to what extent the subsistence and base flows will be met. The software was also designed to keep track of pulse events, so even the most complex three-tile scheme of the environmental flow standards can be evaluated.

1.2.4 Statistical Frequency Analysis to Assess Environmental Flow Standards

Several metrics have been created in past years to analyze the attainment of environmental flow standards and its influence on the other water rights present in each basin using the WAM/WRAP modeling system. The main works have been done by Pauls (2014) and Pauls and Wurbs (2016), where the Trinity River system and the Colorado River system were used for case studies, respectively. In both studies, a daily time step was implemented to run the simulation, which corresponds to the work done in this research.

After reviewing the work done by Pauls (2014) and Pauls and Wurbs (2016), it can be concluded that a total of 10 metrics were defined (Table 1). The other metrics implemented in 2014, which are not included in Table 1, correspond to graphical representations of the metrics.

Table 1 Attainment Metrics for Environmental Flow Standards

	Metric
1	Percentage of time instream flow target is engaged
2	Engaged volume reliability
3	Engaged period reliability
4	Consecutive days instream flow target is engaged
5	Consecutive days instream flow target is engaged and met
6	Consecutive days instream flow target is engaged with a shortage
7	Consecutive days between engagement of an instream flow target
8	Instream flow shortage
9	Instream flow shortage as a percentage of the instream flow target
10	Average instream flow shortage as a percentage of the average instream flow target

The metrics mentioned in Table 1 are computed by considering that a target is engaged every time the flow is between the specified environmental flow standards. Additionally, a flow shortage occurs only if the streamflow is less than the TCEQ standard. Because of these definitions, the metrics have to be individually computed for each gaging station where TCEQ has established environmental flow standards. Moreover, there has to be special care taken when calculating the total amount of days that are used to calculate percentages of time, because the total amount of time changes between river systems and even between gaging stations that are within the same system.

In addition to the metrics presented in Table 1, exceedance frequency plots are valuable tools to compare environmental flow regimes, as demonstrated by Pauls and Wurbs (2016).

Even though the metrics mentioned herein are useful, all of them require extensive manipulation of WRAP output files in Excel macros. However, this research only explores WRAP/WAM capabilities to analyze the effect of environmental flow standards, and the following river systems are used as case studies: Brazos, Trinity, Colorado, Sabine, Guadalupe-San Antonio.

1.3 Research Objectives

This research focused on evaluating and improving WAM capabilities for modeling and analysis of environmental flow requirements and issues. The objectives of the research were as follows:

1. Review the SB3 environmental instream flow standards that have been established to date from the perspectives of their general structure and quantitative metrics adopted to define various aspects of the flow standards and compare the differences and similarities between the flow standards in the different river systems.
2. Evaluate and improve capabilities for incorporating the SB3 environmental flow standards in the WRAP/WAM system.
3. Evaluate the extent to which the environmental flow standards can be expected to be met based on statistical frequency analyses of WAM simulation results.

Frequency metrics and other mechanisms for evaluating attainment of the flow standards were explored.

4. Evaluate the extent to which water availability for municipal, industrial, agricultural, and other water uses are affected by the environmental flow standards based on statistical frequency analyses of WAM simulation results.

The environmental flow standards for the several river systems for which standards have been established to date pursuant to the process authorized by the Texas Legislature in its 1997 Senate Bill 3 were examined in conjunction with the first objective listed above. Modeling and analysis capabilities of the WRAP/WAM system described are addressed by the second objective. The third and fourth objectives involved the application of daily WAMs for the Brazos, Trinity, Colorado, Neches, Sabine, Guadalupe, and San Antonio River systems.

2. SB3 ENVIRONMENTAL FLOW STANDARDS

2.1 Environmental Flow in Texas

The Texas Water Code Title 2, Section 11.002.16, defines an environmental flow as the amount of water that reflects seasonal and yearly fluctuations that are adequate to support a sound ecological environment and to maintain the productivity and extend the persistence of key aquatic habitats. The new environmental flow standards also consider the necessities of the stakeholders; therefore, the environmental flows balance protection of the environment with human needs.

The TCEQ adopted the use of set-asides of unappropriated water to satisfy the environmental flow standards. It should be emphasized that only new water rights or new amendments to existing water rights can be affected by the new standards; the standards are considered junior to all water rights established with dates earlier than the dates associated with each of the new standards.

The TCEQ prioritized a total of seven river systems based on recommendations of science teams and stakeholder committees: Brazos, Trinity, Colorado, Neches, Sabine, Guadalupe, and San Antonio. The process to create, review, and approve the current standards for each of the systems started in 2009 and finished in 2014. The final environmental flow standards for each individual system are presented as subchapters of the Texas Administrative Code, Chapter 298, entitled “Environmental Flow Standards for Surface Water.”

2.2 SB3 Process for Establishing Environmental Flow Standards

The SB3 process is based on regional public participation, and several statewide agencies oversee the process, while technical support is provided by the science community. Local stakeholders and technical experts develop recommendations regarding the appropriate flow regime for particular river systems. The TCEQ, Texas Parks and Wildlife Department, and Texas Water Development Board provide administrative oversight and technical support. Reports and other information created or used are available on the TCEQ websites.

A Basin and Bay Area Stakeholder Committee (BBASC) is appointed for each priority river system. Each BBASC establishes a Basin and Bay Expert Science Team (BBEST) that develops flow regimes based solely on environmental needs. The BBASC reviews the BBEST report and develops environmental flow regimes based on consideration of all water needs. Each BBASC submits a recommendation report to the TCEQ proposing environmental flow standards and a plan for continuing review, monitoring, validation, and refinement. Upon approval, the flow standards are incorporated into the TCEQ WAM system. Priorities are assigned based on the date the TCEQ receives environmental flow regime recommendations from the applicable BBEST. The TCEQ will not issue a permit for a new appropriation or amendment to an existing water right permit that increases the amount of water authorized to be stored, taken, or diverted if any environmental flow standard is violated.

The SB3 environmental instream flow standards are to be reevaluated and modified as appropriate. This process has to occur in review cycles every 5 years.

Additionally, the information that is being developed under the SB2 Texas Instream Flow Program (TIFP) may contribute to future improvements in the SB3 environmental flow standards.

Environmental flow standards adopted by the TCEQ consist of a set of flow metrics and rules that are function of seasons, spatial location, and in some cases hydrologic condition. The standards are defined in terms of flow regimes that describe the magnitude, frequency, duration, timing, and rate of change of flows required to preserve environmental resources. The SB3 process has adopted a framework recommended by studies performed pursuant to the TIFP that defines flow regimes, in several measurement points, that includes four components: subsistence flows, base flows, within-bank high flow pulses, and overbank high flow pulses. These components have already been defined in Section 1.2.1 of this study.

2.3 SB3 Environmental Flow Standards for the Individual River Systems

2.3.1 Trinity and San Jacinto Rivers and Galveston Bay

The final environmental flow standards for the Trinity River system have been in effect since May 15, 2011. The final standards were submitted after the TCEQ evaluated the final versions of the BBEST (November 30, 2009) and BBASC (May 31, 2010) reports developed for this river-bay system. The environmental flow standards were defined at six U.S. Geological Survey (USGS) gaging stations (Table 2).

Table 2 Gaging Stations in Trinity-San Jacinto System

USGS Gage No.	Station Name
08065000	Trinity River near Oakwood
08049500	West Fork Trinity River at Grand Prairie
08066500	Trinity River at Romayor
08057000	Trinity River at Dallas
08068000	West Fork San Jacinto River near Conroe
08070000	East Fork San Jacinto River near Cleveland

The final environmental flow standards vary depending on the season; however, the hydrologic condition was not considered an important factor. The seasons have been defined as follows:

- Fall: The period of time from September through November, inclusive.
- Spring: The period of time from March through May, inclusive.
- Summer: The period of time from June through August, inclusive.
- Winter: The period of time from December through February, inclusive.

The final official legislation document containing the standards for the Trinity and San Jacinto Rivers and Galveston Bay can be found at the following website: http://www.tceq.state.tx.us/assets/public/legal/rules/rules/pdflib/298b.pdf.

2.3.2 Sabine and Neches Rivers and Sabine Lake

The final environmental flow standards for the Sabine and Neches River system have been in effect since May 15, 2011. The final standards were submitted after the TCEQ assessed the final versions of the BBEST (November 2009) and BBASC (May 2010) reports developed for this river-bay system. The environmental flow standards were defined at 10 USGS gaging stations (Table 3).

Table 3 Gaging Stations in the Sabine System

USGS Gage No.	Station Name
08019500	Big Sandy Creek near Big Sandy
08020000	Sabine River near Gladewater
08022040	Sabine River near Beckville
08029500	Big Cow Creek near Newton
08030500	Sabine River near Ruliff
08032000	Neches River near Neches
08033500	Neches River near Rockland
08036500	Angelina River near Alto
08041000	Neches River at Evadale
08041500	Village Creek near Kountze

Environmental flow standards vary depending on season; however, the hydrologic condition was not considered a key factor for the Sabine and Neches River systems. The seasons have been defined as follows:

- Fall: The period of time from October through December, inclusive.
- Spring: The period of time from April through June, inclusive.
- Summer: The period of time from July through September, inclusive.
- Winter: The period of time from January through March, inclusive.

The final document containing the environmental flow standards for the Sabine and Neches Rivers and Sabine Lake Bay can be found at the following website: http://www.tceq.state.tx.us/assets/public/legal/rules/rules/pdflib/298c.pdf.

2.3.3 Colorado and Lavaca Rivers and Matagorda and Lavaca Bays

The final environmental flow standards for the Colorado system have been in effect since August 30, 2012. The final standards were submitted after the TCEQ evaluated the final versions of the BBEST (March 1, 2011) and BBASC (August 2011) developed for this river-bay system. The environmental flow standards were defined at 21 USGS gaging stations (Table 4).

Table 4 Gaging Stations in the Colorado-Lavaca System

USGS No.	Station Name
08123850	Colorado River above Silver
08126380	Colorado River near Ballinger
08127000	Elm Creek at Ballinger
08128000	South Concho River at Christoval
08136500	Concho River at Paint Rock
08143600	Pecan Bayou near Mullin
08146000	San Saba River at San Saba
08147000	Colorado River near San Saba
08151500	Llano River at Llano
08153500	Pedernales River near Johnson City
08158700	Onion Creek near Driftwood
08159200	Colorado River at Bastrop
08161000	Colorado River at Columbus
08162000	Colorado River at Wharton
08164503	West Mustang Creek near Ganado
08164504	East Mustang Creek near Louise
08164390	Navidad near Edna
08164450	Sandy Creek near Ganado
08164000	Lavaca near Edna
08162600	Tres Palacios near Midfield
08164600	Garcitas Creek near Inez

The environmental flow standards that were defined for this system were the first ones that included the importance of both season variability and hydrologic conditions. Thus, the seasons were established as follows:

- Fall: For all the measurement points on the Colorado River and its tributaries above Lake Travis, the period of time from September through October, inclusive, and for all the other measurements points, the period of time from September through November, inclusive.

- Spring: The period of time from March through June, inclusive.
- Summer: The period of time from July through August, inclusive.
- Winter: For the measurement points on the Colorado River and its tributaries above Lake Travis, the period of time from November through February, inclusive, and for all the other measurements points, the period of time from December through February, inclusive.

Likewise, the hydrologic conditions for the Colorado and Lavaca Rivers and Matagorda and Lavaca Bays were defined as follows:

- Average condition: Condition that occurs approximately 50% of the time.
- Dry condition: Condition that occurs approximately 20% of the time and represents periods when conditions are dry but not severe; this only applies to the measurement points above Lake Travis on the Colorado River. On the other hand, for measurement point below Lake Travis on the Colorado River, the dry condition is the hydrologic condition that would occur approximately 45% of the time.
- Wet condition: For all the measurements points on the Colorado River above Lake Travis, the wet condition is the hydrologic condition that occurs approximately 25% of the time and is intended to represent the wettest conditions.

The final document containing the environmental flow standards for the Colorado and Lavaca Rivers and Matagorda and Lavaca Bays can be found at this website: http://www.tceq.state.tx.us/assets/public/legal/rules/rules/pdflib/298d.pdf.

2.3.4 Guadalupe, San Antonio, Mission, and Aransas Rivers and Mission, Copano, Aransas, and San Antonio Bays

The final environmental flow standards for the Guadalupe–San Antonio (GSA) system have been in effect since August 30, 2012. These standards were submitted once the TCEQ reviewed the final BBEST (March 2011) and BBASC (September 2010) developed for this river-bay system. The environmental flow standards were defined at 16 USGS gaging stations (Table 5).

Table 5 Gaging Stations in the GSA System

USGS No.	Station Name
08167000	Guadalupe River at Comfort
08167500	Guadalupe River near Spring Branch
08171000	Blanco River at Wimberley
08172000	San Marcos River at Luling
08173000	Plum Creek near Luling
08173900	Guadalupe River at Gonzales
08175000	Sandies Creek near Westhoff
08175800	Guadalupe River at Cuero
08176500	Guadalupe River at Victoria
08178800	Medina River at Bandera
08181500	Medina River at San Antonio
08181800	San Antonio River near Elmendorf
08183500	San Antonio River near Falls City
08186000	Cibolo Creek near Falls City
08188500	San Antonio River at Goliad
08189500	Mission River at Refugio

The environmental flow standards defined for each of the gaging stations mentioned in Table 5 consider season variability. Nonetheless, the hydrologic condition only affects the standards defined at the last six gaging stations (08181500 to 08189500).

The seasons and hydrologic conditions have been defined as follows:

- Fall: The period of time from October through December, inclusive.
- Spring: The period of time from April through June, inclusive.
- Summer: The period of time from July through September, inclusive.
- Winter: The period of time from January through March, inclusive.
- Average condition: Hydrologic condition that occurs approximately 50% of the time. This condition represents periods that are neither dry nor wet.
- Dry condition: Hydrologic condition that occurs approximately 25% of the time; it represents the driest period.
- Wet condition: Hydrologic condition that occurs approximately 25% of the time; it represents the wettest period.

The final document containing the environmental flow standards for the Guadalupe, San Antonio, Mission, and Aransas Rivers and Mission, Copano, Aransas, and San Antonio Bays can be found at the following website: http://www.tceq.state.tx.us/assets/public/legal/rules/rules/pdflib/298e.pdf.

2.3.5 Nueces River and Corpus Christi and Baffin Bays

The final environmental flow standards for the Nueces River and Corpus Christi and Baffin Bays have been in effect since August 30, 2012. The final standards were submitted after the TCEQ evaluated the final versions of the BBEST (October 2011) and BBASC (August 2012) developed for this river-bay system. The final environmental flow standards were defined at the gaging stations presented in Table 6.

Table 6 Gaging Stations in the Nueces-Corpus System

USGS No.	Station Name
08190000	Nueces River, Laguna
08190500	West Nueces, Brackettville
08192000	Nueces River, Uvalde
08194000	Nueces River, Cotulla
08194500	Nueces River, Tilden
08195000	Frio River, Concan
08196000	Dry Frio River, Reagan Wells
08198000	Sabinal River, Sabinal
08198500	Sabinal River, Sabinal (below Edwards outcrop)
08200000	Hondo Creek, Tarpley
08201500	Seco Creek, Utopia
08204000	Leona Spring, Uvalde
08205500	Frio River, Derby
08206600	Frio River, Tilden
08206700	San Miguel Creek, Tilden
08208000	Atascosa River, Whitsett
08210000	Nueces River, Three Rivers
08211000	Nueces River, Mathis
08211520	Oso Creek, Corpus Christi
08211900	San Fernando Creek, Alice

The environmental flow standards change depending on the season, not the hydrologic condition. Therefore, the seasons were defined as follows for the Nueces River, its associated tributaries, the Nueces-Rio Grande Coastal Basin, and Corpus Christi and Baffin Bays.

- Fall: For the measurement points 3-5, 9, and 12-19, the period of time from September through October, inclusive, and for all other measurement points, the period of time from October through November, inclusive.
- Spring: The period of time from April through June, inclusive.

- Summer: For the measurement points 3-5, 9, and 12-19, the period of time from July through August, inclusive, and for all other measurement points, the period of time from July through September, inclusive.
- Winter: For the measurement points 3-5, 9, and 12-19, the period of time from November through March, inclusive, and for all other measurement points, the period of time from December through March, inclusive.

The final document containing the environmental flow standards for the Nueces River and Corpus Christi and Baffin Bays can be found at the following website: http://www.tceq.state.tx.us/assets/public/legal/rules/rules/pdflib/298e.pdf.

2.3.6 Brazos River and Its Associated Bay and Estuary System

The final environmental flow standards for the Brazos River system have been in effect since March 6, 2014. The final standards were submitted after the TCEQ evaluated the final versions of the BBEST (March 2012) and BBASC (August 2012) reports developed for this system. The final environmental flow standards were defined at the gaging stations presented in Table 7.

Table 7 Gaging Stations in the Brazos System

USGS Gage No.	Station Name
08080500	Double Mountain Fork Brazos River near Aspermont
08082000	Salt Fork Brazos River near Aspermont
08082500	Brazos River at Seymour
08084000	Clear Fork Brazos River near Nugent
08084200	Clear Fork Brazos River near Forth Griffin
08088000	Brazos River near South Bend
08089000	Brazos River near Palo Pinto
08089100	Brazos River near Glen Rose
08095000	North Fork Bosque River at Clifton
08096500	Brazos River at Waco
08100500	Leon River near Gatesville
08103800	Lampasas River near Kempner
08104500	Little River at Little River
08106500	Little River near Cameron
08108700	Brazos River near Bryan
08110500	Navasota River near Easterly
08111500	Brazos River near Hempstead
08114000	Brazos River at Richmond
08116650	Brazos River at Rosharon
08117500	San Bernard River near Boling

The environmental standards change depending on the season and the hydrologic condition. Because of this, the seasons for this river system were defined as follows:

- Spring: The period of time from March through June, inclusive.
- Summer: For all measurement points, the period of time from July through October, inclusive.
- Winter: For all measurement points, the period of time from November through February, inclusive.

Likewise, the hydrologic conditions are:

- Average condition: Hydrologic condition that occurs approximately 50% of the time.

- Dry condition: Hydrologic condition that occurs approximately 25% of the time; it represents the driest period.
- Wet condition: Hydrologic condition that occurs approximately 25% of the time; it represents the wettest period.

The final document containing the environmental flow standards for the Brazos River and its associated bay and estuary system can be found at this website: http://www.tceq.state.tx.us/assets/public/legal/rules/rules/pdflib/298g.pdf.

2.3.7 Rio Grande, Rio Grande Estuary, and Lower Laguna Madre

Due to the size of this system, the TCEQ decided to divide it into the lower and upper Rio Grande. This division allowed the BBEST and BBASC to finish their respective documents within the time constraints. Once the TCEQ reviewed these documents, the final environmental flow standards were submitted, and the effective date was established as March 6, 2014. The standards were established in three IBWCs and one USGS gaging station, as can be seen in Table 8.

Table 8 Gaging Stations in the Rio Grande System

Entity	Gage No.	Station Name
IBWC	08375000	Rio Grande at Johnson's Ranch
IBWC	08377200	Rio Grande at Foster's Weir
USGS	08446500	Pecos River near Girvin
IBWC	08449400	Devils River at Pafford's Crossing

The environmental flow standards were defined as functions of season variability and hydrologic condition. Because of this, the seasons for this river basin were defined as follows:

- Fall: The period of time from July through October, inclusive.
- Spring: The period of time from March through June, inclusive.
- Winter: The period of time from November through February, inclusive.

Likewise, hydrologic conditions are defined as follows:

- Average condition: Hydrologic condition that occurs approximately 50% of the time. This condition represents periods that are neither dry nor wet.
- Dry condition: Hydrologic condition that occurs approximately 15% of the time. This condition represents periods that are dry but are above the subsistence condition.
- Wet condition: Hydrologic condition that occurs approximately 25% of the time; it represents the wettest period.

The complete Subchapter H, which contains the environmental flow standards for the Rio Grande, Rio Grande Estuary, and Lower Laguna Madre, can be found at this website: http://www.tceq.state.tx.us/assets/public/legal/rules/rules/pdflib/298h.pdf

2.4 Comparative Evaluation of the Structure and Metrics Adopted for the Standards

Because of time limitations and the differences between each river basin and bay system, geographic location, water needs, stakeholders, and interstate and international treaties (only for the Rio Grande system), a total of seven BBASCs and seven BBESTs were created—one for each of the river systems. Therefore, the final recommendations received by the TCEQ varied in structure and detail, even though all of them followed similar approaches.

The main differences in the adopted TCEQ rules are related to the way seasons were defined, control points used, and relevance of hydrologic condition. The final environmental flow standards are briefly compared in the following sections.

2.4.1 Definition of Seasons

Due to the extent of each of the river systems, it is reasonable to assume that timing and quantity of seasons associated with a specific geographic location vary greatly. Under this assumption, both the BBESTs and BBASCs defined the seasons for the seven systems, and these recommendations were finally reviewed and approved by the TCEQ, which led to the seasons presented in Table 9.

Table 9 Seasons Defined for Each System

River System	Winter	Spring	Summer	Fall
Trinity-San Jacinto	Dec-Feb	Mar-May	Jun-Aug	Sep-Nov
Sabine-Neches	Jan-Mar	Apr-Jun	Jul-Sep	Oct-Dec
Colorado-Lavaca	Nov-Feb[1] Dec-Feb[2]	Mar-Jun	Jul-Aug	Sep-Oct[1] Sep-Nov[2]
Guadalupe-San Antonio	Jan-Mar	Apr-Jun	Jul-Sep	Oct-Dec
Nueces	Nov-Mar[3] Dec-Mar[4]	Apr-Jun	Jul-Aug[3] Jul-Sep[4]	Sep-Oct[3] Oct-Nov[4]
Brazos	Nov-Feb	Mar-Jun	Jul-Oct	N/A
Rio Grande	Nov-Feb	Mar-Jun	N/A	Jul-Oct

[1] For all the stations above Lake Travis.
[2] All other gaging stations in the Colorado-Lavaca system.
[3] Gaging stations 5, 9, and 12-19 in the Nueces system.
[4] All other gaging stations in the Nueces system that are not mentioned in 3.
N/A = Not applicable.

As can be seen in the information presented in Table 9, the timing of the seasons in each river system changes due to its geographical location. Moreover, it can also be seen that several seasons can occur at the same time in the state (e.g., December corresponds to fall in the Sabine-Neches system, while in some parts of the Colorado-Lavaca and Nueces systems, December is associated with winter). This variation is extremely important because the amount of water associated with the environmental flow standards varies depending on the season.

Additionally, the quantity of seasons also varies between systems; The Brazos and Rio Grande systems only have three seasons. Fall and summer are not considered seasons in the Brazos and Rio Grande system, respectively. The other five systems were defined with four seasons.

2.4.2 Use of Hydrologic Condition and Hydrologic Index

Based on the rulemaking process, the TCEQ determined that the environmental flow standards are affected by hydrologic conditions in only four out of seven river systems. The systems whose standards are influenced by the hydrologic condition are presented in Table 10.

Table 10 Systems Affected by Hydrologic Condition

River System
Colorado and Lavaca Rivers and Sabine Lake Bay
Guadalupe, San Antonio, Mission, and Aransas Rivers and Mission Copano, Aransas, and San Antonio Bays
Brazos River and its Associated Bay and Estuary System
Rio Grande, Rio Grande Estuary, and Lower Laguna Madre

In order to determine the hydrologic condition, four indexes were defined. Each of the indexes was calculated using historic records, which allowed the creation of frequency tables. Once the frequency tables were computed, the indexes were used to define the current hydrologic condition comparing the values established for each river system (Table 11).

Table 11 Frequency Probability to Determine Hydrologic Condition

River Basin and Bay System	Dry	Average	Wet
Colorado and Lavaca Rivers and Sabine Lake Bay	20%[1] 45%[2]	50%	25%
Guadalupe, San Antonio, Mission, and Aransas Rivers and Mission Copano, Aransas, and San Antonio Bays	25%	50%	25%
Brazos River and its Associated Bay and Estuary System	25%	50%	25%
Rio Grande, Rio Grande Estuary, and Lower Laguna Madre	15%	50%	25%

[1] Control point above Lake Travis.
[2] Control points below Lake Travis.

2.4.3 Hydrologic Condition Index

As mentioned in Section 2.4.2, in order to determine the hydrologic condition in the four river systems presented in Table 10, four indexes were developed. The indexes are measured at each of the control points in which environmental flow standards have been implemented by TCEQ. Table 12 presents the four indexes that were developed by the advisory committees and the river systems where the indices have to be implemented.

Table 12 Hydrologic Index by River Basin

River Basin and Bay System	Indicator Use to Define Hydrologic Condition
Colorado and Lavaca Rivers and Sabine Lake Bay	Either cumulative stream flow for previous 12 months, Combined storage of Lake Travis and Lake Buchanan, or Lake Texana elevation. Depends on the location of the gaging station
Guadalupe, San Antonio, Mission, and Aransas Rivers and Mission Copano, Aransas, and San Antonio Bays	Cumulative stream flow for previous 12 months
Brazos River and its Associated Bay and Estuary System	Palmer Hydrologic Drought Index
Rio Grande, Rio Grande Estuary, and Lower Laguna Madre	Cumulative stream flow for previous 12 months

Based on the information presented above, it can be concluded that there is a level of agreement between the BBESTs and BBASCs' members concerning the different river basin and bay systems because three out of four recommended the use of the cumulative streamflow on the previous 12 months. It is valid to underscore that the hydrologic condition has to be determined on the last day of each season.

An important element to be noted is that for the Brazos River-Bay system, the hydrologic condition is not defined at each control point. The system was subdivided into three regions for which the hydrologic condition is determined individually.

2.4.4 Control Points

The control points correspond to gaging stations that were carefully selected by considering factors such as location within the system, information regarding modifications that could have affected the records, and extent of the period of record. Additionally, the advisory committees and the TCEQ decided to consider the versatility of the information in order to select control points that could be used to interpolate environmental flow standards or any other relevant information in (a) locations where there are not gaging stations, or (b) places where environmental flow standards were not defined by the final TCEQ ruling.

Because of the desired characteristics mentioned before, the number of control points selected varies between river basin-bay systems. Table 13 presents the number of gaging stations selected in each system; cumulatively, there are 96 locations where the TCEQ has provided an environmental flow standard.

Table 13 Number of Control Points at Each System

River System	Number of Control Points
Guadalupe-San Antonio	16
Trinity-San Jacinto	6
Rio Grande	4*
Sabine-Neches	10
Colorado-Lavaca	21
Nueces	19
Brazos	20
Total	96

*Gaging stations maintained by the International Boundary and Water Commission.

3. WATER AVAILABILITY MODELING SYSTEM

3.1 WAM/WRAP Modeling System

The WAM system maintained by TCEQ consists of the generalized Water Rights Analysis Package developed at Texas A&M University, which is applicable for river systems located anywhere, and WRAP's input datasets for the river basins of Texas. The WRAP modeling system and input datasets from the TCEQ WAM system for individual river basins are called WAMs. The WAMs for the 15 major river basins and eight coastal basins of Texas simulate a water rights permit system with about 6,200 permits, five interstate compacts, two international treaties, various other agreements between water management entities, and constructed facilities that include 3,400 reservoirs and a variety of conveyance structures, hydroelectric power plants, and other infrastructure (Wurbs, 2015a).

The monthly computational time step in the WRAP/WAM system has been applied by the TCEQ and consulting engineering firms for over a decade in Texas to plan and administrate water rights allocation. The 1997 SB1 mandates that environmental instream flow standards must be incorporated in the WAMs. Research and development at Texas A&M University have focused largely on developing a daily version of the modeling system in order to expand its capabilities to model SB3 environmental instream flow requirements.

The monthly WRAP routinely employed in the TCEQ WAM system is documented by Wurbs (2013, 2015a, 2015b), and the developmental daily WRAP modeling system is documented by Wurbs and Hoffpauir (2013). Monthly and daily simulations may be applied to support a particular decision process. Alternatively, daily instream flow targets computed in a daily simulation can be aggregated to monthly target series for input to a monthly simulation using WRAP features that facilitate this modeling strategy.

The latest publically released version of the WRAP modeling system is dated August 2015. The daily WRAP includes all the capabilities routinely applied in a monthly modeling system as well as an array of major new features: (a) monthly-naturalized flows are disaggregated to daily based on daily pattern hydrographs; (b) reservoir flood control operations are simulated; (c) future days extending over a forecast period are considered in the simulation to determine water availability; (d) routing methods reflecting flow attenuation effects are added; and (e) calibration methods for determining routing parameters are included. The daily WRAP incorporates an expanded array of optional features for simulating instream flow requirements, including high pulse flows.

Development of daily WAMs for the Brazos, Colorado, Trinity, Neches, Sabine, and Guadalupe–San Antonio River systems have been done at Texas A&M University during the research and development process of the daily model. The process of converting the monthly WAMs to daily versions included the addition of the following model components:

- Hydrologic period-of-analysis of each of the WAMs continually being updated, with the most recent versions extending from January 1940 through December 2015.
- Disaggregation of monthly-naturalized flows to daily through flow pattern hydrographs as well disaggregation of other model variables to daily.
- Flow routing and forecasting.
- Simulation of flood control operations of selected large multiple-purpose reservoirs.
- SB3 environmental flow standards.

The new model components are still being tested; therefore, further refinement of the modeling system is expected to occur.

As previously mentioned, the TCEQ maintains the WAM system and provides the monthly WRAP input datasets for all the river basins of Texas. These data sets and an array of relevant information is available at the TCEQ WAM website: http://www.tceq.texas.gov/permitting/water_rights/wr_technical-resources/wam.html. The TCEQ website is linked with the WRAP website maintained at Texas A&M University: https://ceprofs.civil.tamu.edu/rwurbs/wrap.htm.

The WRAP website contains the latest publicly released versions of the WRAP software, manuals, input datasets, documentation for the six case study daily WAMs, and a variety of other technical reports. The six daily WAMs are documented by the following technical reports, that are available in the WRAP website:

- Daily Water Availability Model for the Trinity River Basin (Hoffpauir, Pauls, and Wurbs, 2014).
- Daily Water Availability Model for the Sabine River Basin (Wurbs, Hoffpauir, Pauls, Ryu, & Bista, 2014b).
- Daily Water Availability Model for the Neches River Basin (Wurbs, Hoffpauir, Pauls, Ryu, & Bista, 2014b).
- Daily Water Availability Model for the Guadalupe and San Antonio River Basin (Wurbs, Ryu, Pauls, & Hoffpauir, 2014).
- Application of Expanded WRAP Modeling Capabilities to the Colorado WAM (Hoffpauir, Pauls, & Wurbs, 2013).
- Application of Expanded WRAP Modeling Capabilities to the Brazos WAM (Wurbs, Hoffpauir, & Schnier, 2012).

The simulation studies reported in Sections 4, 5, and 6 of this thesis employed the WRAP software, documentation, and daily WAM datasets available at the WRAP website. Updated editions of the WRAP software and manuals and daily WAM datasets will be publically released later in 2017. The remainder of Section 3 briefly summarizes information from the reports cited in the preceding paragraph describing the six case study water availability models (WAMs).

3.2 Daily Water Availability Models for the Selected River Systems

The TCEQ WAM system includes a total of 20 WAMs that model the 15 major river basins and eight coastal basins delineated by the TWDB (Figure 1).

Figure 1 Major River Basins Defined by the TWDB

The following subsections (3.2.1 to 3.2.5) provide a brief description for each WAM data set whose environmental flow standards have been established by the TCEQ through the lawmaking process. Therefore, the following systems are presented next: (a) Trinity; (b) Sabine; (c) Colorado; (d) Guadalupe and San Antonio; (e) Neches; and (f) Brazos.

3.2.1 Trinity and San Jacinto Rivers and Galveston Bay

The Trinity WAM is under constant update by the TCEQ, which keeps track of all the water right permit applications that are approved. Moreover, the constant refinements in modeling techniques also play a role in the varying number of system components. For instance, the original authorized WAM only modeled 552 water rights, while the last version (October 2015) included 71 instream flow (IF) records and 1057 water rights (WR) records.

Among the largest water right holders are Dallas Water Utilities, Trinity River Authority, and the North Texas Municipal Water District, which makes sense considering the extent and location (see Figure 2) of the Trinity River system, wherein Dallas–Fort Worth is the largest metropolitan area.

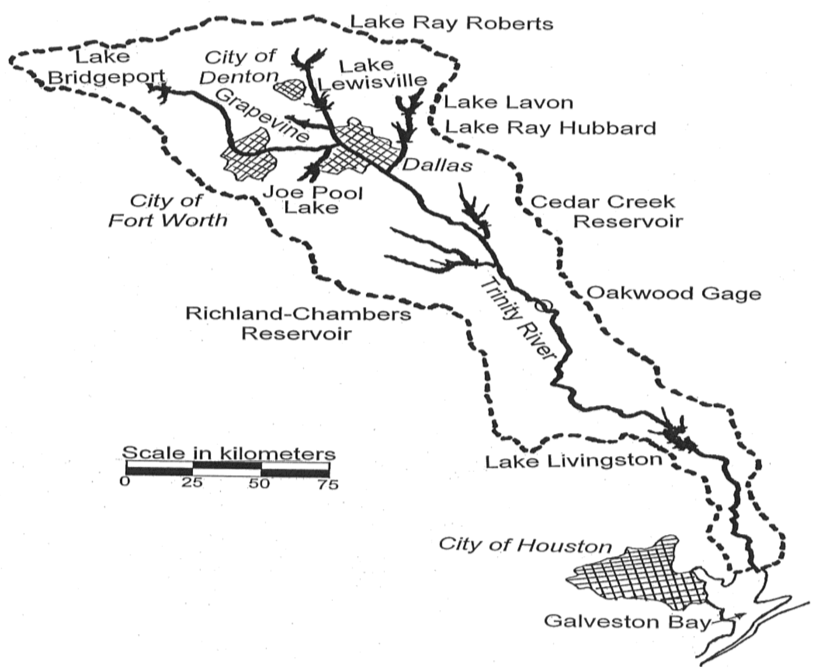

Figure 2 Trinity River System (Wurbs, 2017f)[1]

[1] Reprinted with permission from *Hydrology Update for the Trinity River Basin Water Availability Model*, by R. A. Wurbs, 2017, Texas Water Resources Institute, College Station, TX. Copyright 2017 by R. A. Wurbs.

Moreover, 697 reservoirs are included in the Trinity WAM, which accounts for a total conservation capacity of 7,596,680 acre-feet. About 98% of the total storage capacity is allocated in 32 major reservoirs. The USACE owns and operates eight reservoirs (Ray Roberts, Lewisville, Lavon, Joe Pool, Grapevine, Benbrook, Navarro Mills, and Bardwell), Lewisville and Benbrook have the biggest and smallest flood control capacity, respectively. The total flood control capacity after adding up all the flood pools is 1,620,710 acre-feet.

The Trinity WAM has 30 primary control points that correspond to the location of USGS stream gaging stations. Thus, stream data is available at each of these locations, with the exception of the control point located at the outlet of the Trinity River at Galveston, where there is not a gaging station.

3.2.2 Sabine and Neches Rivers and Sabine Lake

The largest city in the system is Longview, located on the northwest side of the system. The official Sabine WAM has 375 control points, but only 27 are primary (Figure 3). Moreover, 18 of these control points correspond to USGS stream gaging stations, while the remaining nine control points are used for accounting purposes.

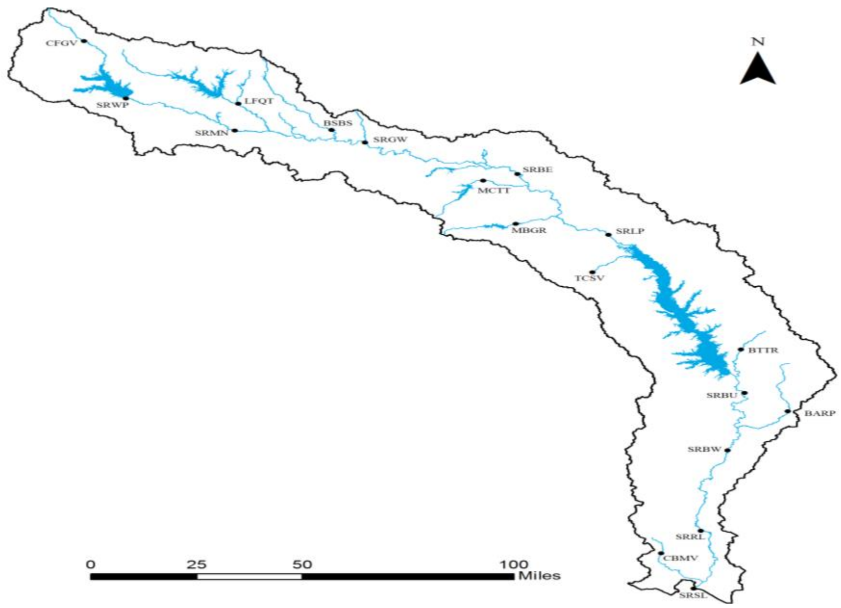

Figure 3 Sabine River System (Wurbs, 2017c)[2]

The latest version of the Sabine WAM includes 207 reservoirs in the authorized-use scenario, but only 13 of these are considered major reservoirs, so they have storage capacities exceeding 5,000 acre-feet. The total permitted conservation storage of the major reservoirs accounts for 99% of the total storage capacity, 6,401,010 acre-feet, in the 207 reservoirs within the system.

The latest authorized-use scenario for the Neches WAM dataset has 396 control points, out of which 20 are primary (Figure 4). This data set contains 385 WR records, 78 IF records, and 180 reservoirs.

---

[2] Reprinted with permission from *Hydrology Update and Refinement for the Sabine River Basin Daily Water Availability Model*, by R. A. Wurbs, 2017, Texas Water Resources Institute, College Station, TX. Copyright 2017 by R. A. Wurbs.

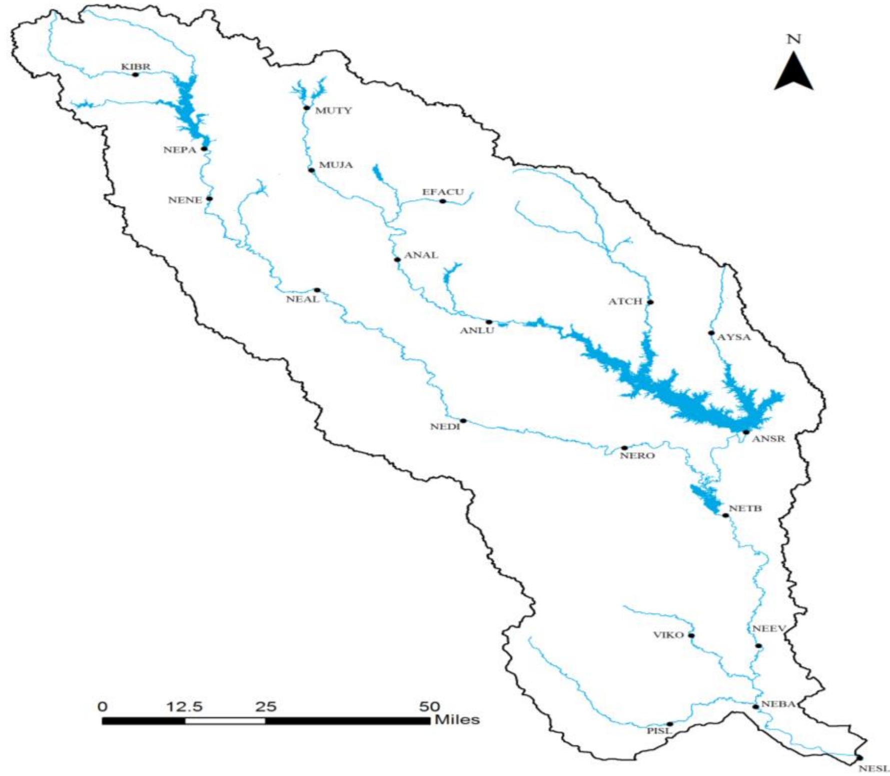

Figure 4 Neches River System (Wurbs, 2017b)[3]

The total storage capacity of the 180 reservoirs located in the system is 3,904,101 acre-feet, but approximately 99% of this volume is stored in 13 reservoirs.

3.2.3 Colorado and Lavaca Rivers and Matagorda and Lavaca Bays

The latest official version of the Colorado WAM was updated in March 2010 and contains a total of 2,422 control points, out of which 45 are primary control points. This version has 2,006 WR records and 99 IF records. Additionally, the Colorado WAM has

[3] Reprinted with permission from *Hydrology Update and Refinement for the Neches River Basin Daily Water Availability Model*, by R. A. Wurbs, 2017, Texas Water Resources Institute, College Station, TX. Copyright 2017 by R. A. Wurbs.

31 dummy reservoirs that do not exist in reality but were included to facilitate modeling processes due to the complexity of some water rights.

The Colorado system was divided into the Upper and Lower Colorado systems (Figure 5) due to the size and characteristics that are present in the system. Moreover, Figure 5 presents some of the most important tributaries and largest reservoirs (by storage capacity) that form the system.

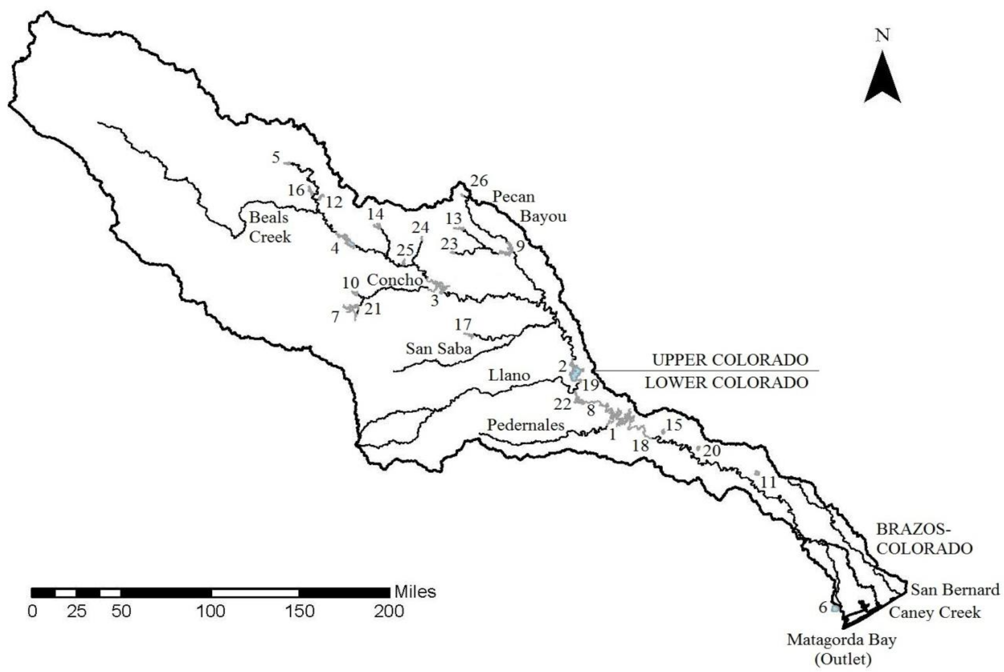

Figure 5 Colorado River System (Wurbs, 2017e)[4]

The total storage capacity of the 487 reservoirs located in the system is 5,313,882 acre-feet, but approximately 98% of this volume is stored in 31 major

---

[4] Reprinted with permission from *Hydrology Update for the Colorado River Basin Water Availability Model*, by R. A. Wurbs, 2017, Texas Water Resources Institute, College Station, TX. Copyright 2017 by R. A. Wurbs.

reservoirs. In total, the total number of reservoirs in the Colorado WAM is 518, after including the dummy reservoirs previously mentioned.

3.2.4 Guadalupe, San Antonio, Mission, and Aransas Rivers and Mission, Copano, Aransas, and San Antonio Bays

The two major tributaries in this system are the Guadalupe and San Antonio Rivers, which are modeled through 46 primary control points and over 1,290 secondary control points in WAM (Figure 6). Twenty-two of the primary control points are in the Guadalupe River system, while the others are located in the San Antonio River system.

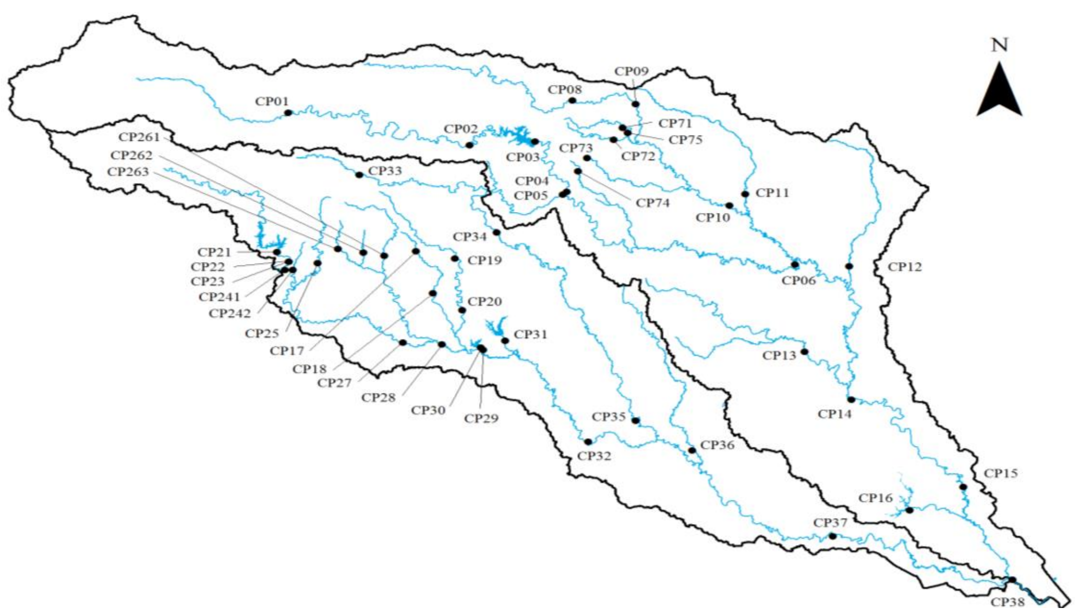

Figure 6 GSA Rivers System (Wurbs, 2017a)[5]

[5] Reprinted with permission from *Hydrology Update and Refinement for the GSA River Basin Daily Water Availability Model*, by R. A. Wurbs, 2017, Texas Water Resources Institute, College Station, TX. Copyright 2017 by R. A. Wurbs.

A total of 238 reservoirs are included in the GSA WAM; however, 96% of the permitted conservation capacity is contained in nine major reservoirs. The latest GSA WAM data set contains 872 WR records, 214 IF records, and 13 control points with precipitation and evaporation rates. The total area covered by this system is 10,100 square miles.

3.2.5 Brazos River and Its Associated Bay and Estuary System

The Brazos WAM is under constant update by the TCEQ, which keeps track of all the water right permit applications that are approved. The current work of the TCEQ in the Brazos WAM consists of eliminating unnecessary control points as well as adding reservoirs within the system. The latest Brazos WAM version contains 3,852 control points that are used to model 1734 water rights and 145 IF records. It is important to note that there are only 77 control points, and only 10 of these do not contain precipitation and evaporation information stored in the evapotranspiration (EV) records.

The Brazos River system contains about 700 reservoirs, but only 16 of these have a combined conservation and flood storage capacity greater than 75,000 acre-feet. The main reservoirs and tributaries within the Brazos River system are presented in Figure 7.

Figure 7 Brazos River System (Wurbs, 2017d)[6]

The reservoirs presented in Figure 7 account for 79.7 and 80.7% of the total conservation storage capacity available in the Brazos River, for the authorized- and current-use scenario, respectively. The USACE owns and operates nine reservoirs whose conservation pools have been contracted by the BRA.

Importantly, all the water diversion in the system is distributed at a rate of 47.6, 30.1, 18.0, 4.3% for municipal, industrial, agriculture, and other uses, respectively (Wurbs, 2017d).

[6] Reprinted with permission from *Hydrology Update for the Brazos River Basin Water Availability Model*, by R. A. Wurbs, 2017, Texas Water Resources Institute, College Station, TX. Copyright 2017 by R. A. Wurbs.

3.3 Modeling SB3 Environmental Flow Standards in the WRAP/WAM System

3.3.1 Modeling SB3 Flow Standards in Daily Simulation

As mentioned before, the creation of SB3 environmental flow standards motivated the expansion of WRAP capabilities in order to model base, subsistence, and pulse flows. Base and subsistence flows are modeled using a combination of WR, target options (TO), daily options (DO), flow switch (FS), and daily water (DW) rights input data records. Therefore, modeling environmental flows, even in the simplest case (Trinity River system), can prove to be a lengthy and complicated process due to the number of input records that have to be written in the .DAT file.

The following procedure is a brief explanation of the methodology used to model base and subsistence flows:

1. Define a WR record with the priority date for the SB3 (defined by TCEQ), establish a dummy value for the target, and set up a group identifier.
2. Define a TO record using the minimum target required by TCEQ. Use DO records to provide supplemental information regarding the target.
3. Repeat the previous steps for each season while considering base and subsistence flows.
4. Group all the TO records previously created using the maximum value option for each target.
5. Repeat the previous steps for each control point that has environmental flow standards.

A similar procedure is required to model pulse flow events, but PF and PO records are used.

As an example, Figure 8 and Figure 9 present the input records required to model the SB3 standards following the procedure described above. The environmental flow standards that are being modeled correspond to standards that were defined by TCEQ (Table 14) for the gaging station 08049500 located at West Fork Trinity River near Grand Prairie.

Table 14 Environmental Flow Standards at West Fork Trinity River near Grand Prairie, Trinity River System

Season	Subsistence (cfs)	Base (cfs)	Pulse
Winter	19	45	Trigger: 300 cfs Volume: 3,500 af Duration: 4 days
Spring	25	45	Trigger: 1,200 cfs Volume: 8,000 af Duration: 8 days
Summer	23	35	Trigger: 300 cfs Volume: 1,800 af Duration: 3 days
Fall	21	35	Trigger: 300 cfs Volume: 1,800 af Duration: 3 days

```
** Environmental Flow Standards for Control Point
** 8WTGPE, USGS 08049500, West Fork Trinity River near Grand Prarie
**
**
WR8WTGPE    99999  WINTER20091201    8                             8WTGPE_SUB_WIN
TO     15   37.69     MIN
DO         16
WR8WTGPE   267.77  WINTER20091201    8                             8WTGPE_BASE_WIN
FS      1             0.0      1.0          89.26    1            0            1
DO                 19
DW          2
WR8WTGPE    99999  SPRING20091201    8                             8WTGPE_SUB_SPR
TO     15   49.59     MIN
DO         16
WR8WTGPE   267.77  SPRING20091201    8                             8WTGPE_BASE_SPR
FS      1             0.0      1.0          89.26    1            0            1
DO                 19
DW          2
WR8WTGPE    99999  SUMMER20091201    8                             8WTGPE_SUB_SMR
TO     15   45.62     MIN
DO         16
WR8WTGPE   208.26  SUMMER20091201    8                             8WTGPE_BASE_SMR
FS      1             0.0      1.0          69.42    1            0            1
DO                 19
DW          2
WR8WTGPE    99999    FALL20091201    8                             8WTGPE_SUB_FAL
TO     15   41.65     MIN
DO         16
WR8WTGPE   208.26    FALL20091201    8                             8WTGPE_BASE_FAL
FS      1             0.0      1.0          69.42    1            0            1
DO                 19
DW          2
WR8WTGPE        0        20091201    8                             8WTGPE_BASEFLOW
TO     13             MAX                                  8WTGPE_SUB_WIN      CONT
TO     13             MAX                                  8WTGPE_SUB_SPR      CONT
TO     13             MAX                                  8WTGPE_SUB_SMR      CONT
TO     13             MAX                                  8WTGPE_SUB_FAL      CONT
TO     13             MAX                                  8WTGPE_BASE_WIN     CONT
TO     13             MAX                                  8WTGPE_BASE_SPR     CONT
TO     13             MAX                                  8WTGPE_BASE_SMR     CONT
TO     13             MAX                                  8WTGPE_BASE_FAL
DO         16
```

Figure 8 SIMD Input Records for Subsistence and Base Flow Standards at West Fork Trinity River near Grand Prairie

```
WR8WTGPE       0        20091201   8                              8WTGPE_PULSE
PF     0        595.04     1800   3   2         6  11          2   4                    8WTGPE_SMRFAL
PO             2
PF     0        595.04     3500   4   2        12   2          2   4                    8WTGPE_WINTER
PO             2
PF     0       2380.17     8000   8   2         3   5          2   4                    8WTGPE_SPRING
PO             2
IF8WTGPE                20091201   2          IF-8WTGPE
TO    13             MAX                              8WTGPE_BASEFLOW     CONT
TO    13             MAX                              8WTGPE_PULSE
DO        16
**
**----------------------------------------------------------------------------------------------
```

Figure 9 SIMD Input Records for Pulse Flow Standards at West Fork Trinity River near Grand Prairie

Further detail regarding the capabilities of each record that can be used to perform daily simulations considering environmental flow standards are found in the report entitled *Environmental Flows in Water Availability Modeling* (Wurbs & Hoffpauir, 2013) as well in the *WRAP Daily Modeling System Manual* (Wurbs & Hoffpauir, 2015).

3.3.2 Converting Simulated Daily Targets to Monthly Targets

The monthly WRAP/WAM modeling system is routinely applied by water management professionals in Texas in planning and water right permitting activities. The daily modeling system is extremely complex but is required to accurately model the SB3 flow standards, particularly the pulse flow components. A strategy is explored in which the daily modeling system is applied by experts to develop environmental flow quantities for incorporation in the monthly SIM simulation input datasets.

A methodology previous proposed by Wurbs and Hoffpauir (2013) is employed in Section 5 of this thesis in which instream flow targets are computed with the daily

SIMD simulation model, aggregated to monthly totals, and provided as input to the monthly *SIM* simulation model. The daily targets computed in the daily *SIMD* simulation are summed to monthly target volumes within *SIMD*. The resulting sequences of monthly target volumes from the *SIMD* simulation results are inserted in the monthly *SIM* input dataset as target series *TS* records in a TSF file. Since subsistence, base, and pulse flow targets are interdependent, the final daily targets considering all components are reflected in the adopted monthly totals.

The strategy of computing monthly instream flow targets with a daily *SIMD* simulation for inclusion in the input dataset for a monthly *SIM* simulation provides the correct quantities for the monthly target volumes. However, since the monthly regulated flows limits are being applied in a monthly simulation, the effects on other more junior water rights are still subject to the impreciseness of a monthly computational time step. Combining the monthly and daily simulations greatly improves the accuracy of the monthly simulation but does not completely resolve preciseness issues. An example of applying the methodology is presented in the following section, where a small system is used to show the basic procedure. Further detail is presented in by Wurbs and Hoffpauir (2013). The proposed methodology is also applied for the larger river systems such as Trinity, Sabine, and Neches as can be seen in Section 5.

The August 2015 versions of the WRAP software and daily WAM datasets were employed in the thesis research. The next version of WRAP and the WAM datasets to be released layer in 2017 will incorporate improvements for modeling SB3 environmental flow standards. These improvements will include use of Hydrologic Engineering Center

(HEC) Data Storage System (DSS) capabilities for storing targets computed in a daily simulation as input for monthly simulations.

3.3.3 Proposed Modeling Approach Example

The dataset of example 8.1 and 8.2 from the *Daily Manual* (Wurbs & Hoffpauir, 2015) was used to perform the simulation with the proposed combined daily and monthly. Once the daily simulation has been completed, the WRAP program HYD is run using the input file presented in Figure 10 in order to get the monthly instream flow target series.

```
JC   1940   58    1
OI     18    2   TS
ED
```

Figure 10 HYD Input File for Creating TS Records

The monthly target series is included in the monthly simulation using a TS record (Figure 11) that specifies the control point where these targets should try to be met.

```
** Instream Flow Requirements at Hempstead Gage   *!*******!*******!*****
IF  Hemp       0               0 1 2           HEMP-ENVIROFLOW
TS       TSF emp
```

Figure 11 SIM Input Modification in the IF Record to Include TSF File

Once the monthly .DAT file has been modified to include instream flow targets, the simulation is performed and the pertinent analysis regarding environmental, unappropriated, regulated, and naturalized flows can be performed as in any other monthly simulation. In this case, only the magnitude and frequency of the shortages is presented to identify the way in which these values can be computed through the .TIN file (Figure 12). Moreover, Table 15 presents the instream flow shortages computed with this approach.

```
2FRE    8    0    0
2IFT    1    4    0    0    1         0
IDEN    Hemp
2IFS    1    4    0    0    1         0
IDEN    Hemp
2REG    1    4    0    0    1         0
IDEN    Hemp
ENDF
```

Figure 12 SIM Input TIN File

Year	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1940	1168	1093	1577	2162	15662	3695	2128	1819	1805	1319	1611	3727
1940	176700	165300	210800	204000	368644	282600	148000	124000	120000	124000	1302747	176700
1941	176700	159600	483200	204000	210800	204000	124000	145759	140210	124000	219900	176700
1942	176700	159600	210800	480269	210800	204000	136000	125305	135846	124000	219900	176700
1943	250139	159600	210800	204000	210800	204000	62418	45154	44618	65019	43535	53443
1944	137449	125501	397875	75938	927472	86178	147915	124000	140147	124000	231176	62000
1945	61323	56000	433868	204000	210800	204000	159919	124000	120000	124000	151242	270738
1946	62000	56000	210800	282600	210800	360367	124000	147617	140305	124000	252739	62000
1947	62000	56000	287815	351200	210800	204000	124000	160000	120000	124000	39011	49943
1948	40565	156127	73693	81753	73108	55956	103445	32440	37741	31057	32842	32788
1949	52631	45348	93000	240000	258670	76834	46056	27778	52192	86910	60000	62000
1950	62000	233598	80464	120000	186537	188856	34500	75591	65444	30000	25056	26562
1951	29867	47789	51800	45391	53708	47739	27465	43640	35523	26712	25688	25154
1952	23953	30852	42109	118832	204789	67616	29198	23324	28154	23626	36470	47477
1953	158806	35520	93000	47886	1185948	66920	85854	23250	22500	34592	40000	267558
1954	47863	29653	25402	45958	239636	22500	23250	23250	22500	27976	32754	23564
1955	30691	48137	40047	83423	236906	64415	23250	28500	28724	44750	28853	24289
1956	24370	47684	34734	32468	244024	28710	23354	24972	22500	25966	31536	53232
1957	23250	34352	67479	1232123	187065	90000	142000	144000	120000	124000	274248	176700
1958	176700	159600	376003	204000	315600	204000	157582	124000	120000	124000	171000	176700
1959	176700	234623	50745	238309	279379	75320	83523	46354	34851	1017418	171000	322411
1960	176700	165300	210800	204000	370284	308800	109949	38520	28613	70762	196367	62000
1961	62000	56000	360941	204000	210800	308800	166000	124000	120000	124000	229606	241306
1962	176700	159600	151494	60666	57800	63000	101061	24750	31024	46500	82317	125117
1963	47167	142540	40546	76096	41475	38884	33512	23267	22610	31097	42468	44476
1964	47862	36283	83660	54531	60286	47641	42010	30270	64930	38123	150571	58057
1965	119109	56000	93000	84879	1208224	90000	124000	124000	140484	141537	160266	161688
1966	62000	56000	282941	178854	93000	85041	124000	163712	120000	124000	171000	176700
1967	176700	159600	32282	60388	69917	59284	29846	24469	36260	33585	160752	54103
1968	173000	58000	424785	204000	210800	204000	168882	124000	120000	124000	203600	216460
1969	176700	241100	428535	118117	93000	88836	124000	124000	120000	124000	50736	173291
1970	60161	167000	319883	345975	210800	204000	124000	124000	138878	148000	44650	38389
1971	39447	46532	49813	56107	91871	36544	79926	47922	22500	35180	128457	173897
1972	62000	57366	51864	50484	248958	54848	46500	53274	22500	61814	82220	72846
1973	102000	45321	256121	180875	93000	90000	79261	43869	44132	542860	275541	83609
1974	62000	56000	79306	62181	73883	37746	46500	109637	44617	30908	140000	62000
1975	48916	56000	351200	378400	210800	204000	164337	124000	120000	124000	171000	176700
1976	176700	165300	61918	180000	93000	234314	160083	41265	41119	45975	60000	155360
1977	62000	136000	119600	276530	315600	204000	124000	124000	120000	124000	37604	41804
1978	41605	146818	68540	59339	45646	56105	25161	83762	22500	23250	22500	23250
1979	172129	156000	247779	213886	93000	90000	171354	124000	120000	124000	43783	54308
1980	62000	165000	93000	90000	366559	42167	40427	30848	68227	48175	22500	23250
1981	23250	41000	75681	57811	93000	1296720	222134	40710	33820	40739	167000	50141
1982	40720	49110	84445	90000	137334	267183	111763	26767	27987	27765	34581	51083
1983	152954	115309	267075	68976	201411	88868	35925	111500	45000	32250	25601	41118
1984	39678	38008	82037	35678	42252	36039	29868	26626	26390	694725	221327	62000
1985	45381	56000	200075	68215	200152	55380	31178	23370	26553	100247	136785	122000

Figure 13 Instream Target Series at Control Point Hemp (acre-feet)

Year	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1986	62000	56000	72404	64181	239486	210000	104000	69086	77093	34383	50000	130642
1987	62000	167679	375751	204000	335746	1184332	173614	124000	120000	124000	147372	153911
1988	47000	48291	69953	66133	49293	76266	42585	38586	30893	23250	24594	32357
1989	62000	46523	88558	80778	213000	187589	79000	78869	33911	23882	35981	30976
1990	57539	56000	286519	176774	81750	212000	142057	124000	144000	124000	171000	176700
1991	209300	224800	93000	263795	272295	42750	40218	92188	32512	43500	123700	232838
1992	176700	165300	210800	308800	237000	335000	144000	142301	120000	124000	171000	258200
1993	201119	159600	462515	204000	210800	204000	147955	124000	120000	136000	47564	50114
1994	52510	55357	89325	55708	331998	45000	69964	39739	51917	55000	123590	102000
1995	61313	52805	198998	264166	69013	80262	106500	110223	40274	36460	36423	55484
1996	38739	42592	42214	67548	34359	54822	40875	94513	42750	38903	48404	62000
1997	62000	96000	210800	1222798	426948	204000	159911	124000	120000	124000	171000	306702

Figure 13 Continued

Table 15 Instream Flow Shortages (acre-feet/month)

Water Right	**Mean**	**Standard Deviation**	**Percentage of Months with Shortage Equaling or Exceeding Values Shown**					
			100%	90%	60%	40%	10%	Maximum
Hemp-EF	3,519	16,963	0	0	0	0	0	155,304

Even though the shortages associated with the percentages shown above (Table 15) are zero, the instream flow requirements are not met all the time. This is evident in the fact that both the mean and maximum shortages are greater than zero. Therefore, in this example, instream flow shortages occur less than 10% of the time but are great enough to make the mean shortage over 3,500 acre-feet/moth. Furthermore, if a daily simulation were implemented, the magnitude and frequency of the shortage would decrease.

4. ATTAINMENT OF ENVIRONMENTAL FLOW STANDARDS

The August 2015 version of the WRAP daily simulation model SIMD was executed with the river basin input datasets described in the technical reports cited in the previous section. The simulations were performed using a daily computational time step. Daily simulation results were aggregated within SIMD to time series of monthly volumes and frequency analyses were performed for both the daily simulation results and monthly summations of the daily simulation results.

The simulations are based on the premise that all water users use the full amounts of water authorized by their water right permits with authorized reservoir storage capacities during a simulated repetition of historical natural hydrology. The 2014-2015 versions of the Trinity, Sabine, Neches, Colorado, and Brazos WAMs used in the thesis research have hydrologic periods-of-analysis of 1940-2013. The Guadalupe-San Antonio (GSA) WAM has a 1934-2013 period-of-analysis.

The Trinity, Sabine, Neches, Colorado, GSA, and Brazos WAMs incorporate SB3 environmental flow standards at four, five, five, fourteen, fifteen, and nineteen USGS gauging stations (WAM control points), respectively. These SB3 environmental flow standards were modeled using dummy control points located down streams of the gaging stations where environmental flow standards are defined. These dummy control points have the letter “E” at the end of their identifier, and the flow standards associated with each control point have the name of the dummy control point. The WAM identifier and gaging station name for each of the control points used to model SB3 environmental flow standards in all the daily WAMs are presented in Table 16 to 21.

Table 16 Control Point Names and Identifier in Trinity WAM

WAM Identifier	Station Name
8WTGPE	West Fork Trinity River near Grand Prairie
8TRADE	Trinity River at Dallas
8TROAE	Trinity River near Oakwood
8TRROE	Trinity River at Romayor

Table 17 Control Point Names and Identifier in Sabine WAM

WAM Identifier	Station Name
BSBSE	Big Sandy Creek near Big Sandy
SRGWE	Sabine River near Gladewater
SRBEE	Sabine River near Beckville
29500E	Big Cow Creek near Newton
SRRLE	Sabine River near Ruliff

Table 18 Control Point Names and Identifier in the Sabine WAM

WAM Identifier	Station Name
NENEE	Neches River near Neches
NEROE	Neches River near Rockland
ANALE	Angelina River near Alto
NEEVE	Neches River at Evadale
VIKOE	Village Creek near Kountze

Table 19 Control Point Names and Identifier in Colorado WAM

WAM Identifier	Station Name
B2000E	Colorado River above Silver
C3000E	South Concho River at Christoval
C1000E	Concho River at Paint Rock
D4000E	Colorado River near Ballinger
D3000E	Elm Creek at Ballinger
E1000E	San Saba River at San Saba
F2000E	Pecan Bayou near Mullin
F1000E	Colorado River near San Saba
G1000E	Llano River at Llano
H1000E	Pedernales River near Johnson City
J5000E	Onion Creek near Driftwood
J3000E	Colorado River at Bastrop
J1000E	Colorado River at Columbus
K2000E	Colorado River at Wharton

Table 20 Control Point Names and Identifier in GSA WAM

WAM Identifier	Station Name
CP01E	Guadalupe River at Comfort
CP02E	Guadalupe River at near Spring Branch
CP08E	Blanco River at Wimberley
CP10E	San Marcos River at Luling
CP11E	Plum Creek near Luling
C3846E	Guadalupe River near Gonzales
CP13E	Sandies Creek near Westhoff
CP14E	Guadalupe River at Cuero
CP15EE	Guadalupe River at Victoria
P3824E	Medina River at Bandera
CP28E	Medina River at San Antonio
CP29E	San Antonio River near Elmendorf
CP32E	San Antonio River near Falls City
CP35E	Cibolo Creek near Falls City
CP37E	San Antonio River at Goliad

Table 21 Control Point Names and Identifier in Brazos WAM

WAM Identifier	Station Name
SFAS0E	Salt Fork Brazos River near Aspermont
DMAS0E	Double Mountain Fork Brazos River near Aspermont
BRSE1E	Brazos River at Seymour
CFNU1E	Clear Fork Brazos River at Nugent
CFFG1E	Clear Fork Brazos River at Fort Griffin
BRSB2E	Brazos River near South Bend
BRPP2E	Brazos River near Palo Pinto
BRGR3E	Brazos River near Glen Rose
NBCL3E	North Bosque River near Clifton
BRWA4E	Brazos River at Waco
LEGT4E	Leon River at Gatesville
LAKE5E	Lampasas River near Kempner
LRLR5E	Little River at Little River
LRCA5E	Little River near Cameron
BRBR5E	Brazos River at SH 21 near Bryan
NAEA6E	Navasota River near Easterly
BRHE6E	Brazos River near Hempstead
BRRI7E	Brazos River near Richmond
BRRO7E	Brazos River near Rosharon

The instream flow targets associated with the subsistence, base, and high flow pulse components of the SB3 environmental flow standards at each control point are computed and summed within SIMD for each day of the simulation. Shortages in meeting the targets are computed each day as regulated stream flow less instream flow target. The SIMD model automatically creates two output files. The daily simulation results file includes the daily target and shortage volumes along with many other simulation results time series variables. The monthly output file contains monthly summations or means of the daily simulation results.

The statistical frequency capabilities of a WRAP post-simulation program were used in order to evaluate the extent to which environmental flow standards can be expected to be met. Specifically, the 2FRE (monthly) and 6FRE (daily) record frequency analysis features were used to estimate instream flow shortage-frequency relationships for the results obtained from simulations computed using a daily time step. The frequency analysis consists of the following steps which are performed within the WRAP software:

1. Sort out all the instream flow shortages.
2. Compute the exceedance frequency of the shortages (Equation 1):

$$Exceedace\ Frequency = \frac{n}{N} * 100$$ **Equation 1**

$Where,$

$n = number\ of\ months\ or\ days\ where\ a\ flow\ is\ equal\ or\ exceeded$

$N = Total\ number\ of\ months\ or\ days\ in\ the\ simulation$

3. In case the frequency does not match a flow value, linear interpolation is used to determine the shortage related to the specific frequency.

Once all the shortages associated with the desired frequency were computed, the results were tabulated, including the maximum and mean instream flow shortage. The only value that is common and that can be compared between the daily and monthly analysis is the mean shortage, which in the monthly simulation corresponds to the mean daily shortage times the number of days in a month (approximately 30.4). Frequency-shortage relationships are not directly comparable because the monthly analysis adds up all the shortages in each month and then sorts them to later use Equation 1; hence, the number of shortages increases because a month presents a shortage even if only 1 day in that month does not attain SB3 environmental flow standards. Therefore, the magnitude and the number of shortages change drastically between monthly and daily analysis.

In order to analyze the attainment of pulse flows, the tracking option in the PF record was activated; therefore, SIMD output provided the total quantities of initiated, terminated, and completed pulse flows for each month in the simulation. A theoretical number of pulse flows has been computed for each control point mentioned in the Texas Administrative Code Chapter 298. Consequently, the attainment of these events can be seen as the percentage of the theoretical number (Equation 2).

$$Pulse\ flow\ attainment = \frac{number\ of\ completed\ pulse\ events\ in\ the\ simulation}{theoretical\ number\ of\ pulse\ events} * 100\%$$

Equation 2

The theoretical number of pulse events is equal to the total number of events that have to occur in one year at each control point, in accordance with SB3 flow standards, times the number of years in the simulation. This methodology was applied to all the river systems, but it was slightly modified for the Brazos system because the amount and type of pulses change depending on the hydrologic condition.

The simulations were performed using a daily time step with flow routing and forecasting in order to increase accuracy in the modeling process as well as in the simulation results. Although this increases the computational time, it is cogent to use this level of detail in order to properly evaluate the level at which environmental flow standards are expected to be met. The metrics previously mentioned have been computed for each of the WAMs discussed in Section 3.2 using the results obtained from SIMD and are presented in the following paragraphs.

After running the simulations and identifying the water rights relevant to this study, the shortage-frequency analysis was performed for the aggregated monthly shortage volumes (Table 22 to Table 27) generated in a daily simulation that includes the

SB3 environmental flow standards. The shortage-frequency metrics performed for the Trinity, Sabine, Neches, Colorado, and Brazos WAMs were done considering a hydrologic period of analysis of 1940-2013 (888 months). The hydrologic period of analysis for the GSA WAM corresponds to 960 months (1934-2013).

Based on the frequency analyses, it is possible to conclude that both the frequency and magnitude of the instream flow shortages vary geographically within each system. The mean instream flow shortages can be as high as 97% (CP29E in the GSA system) and as low as 0.32% (SRBEE in the Sabine system) of the mean target. Depending on the control point and system that is being analyzed, an instream shortage with a frequency of 10% can equal 97% of the mean target, as seen in the control point CP32E in the Colorado system.

In addition to the aggregated monthly shortage volumes, daily shortage volumes (Table 28 to Table 33) were also computed for all the simulations. The results from these analyzes are not comparable to the aggregated monthly shortage volumes (Table 22 to Table 27) because one metric is based on counting the percentage of months, while the other counts the percentage of days. The daily shortage volumes have been used to determine the amount of time with a non-zero shortage for all case studies (Table 34). The percentage of time with shortages ranges from 40% to 90% among the systems, with the GSA being the most critical case.

Table 22 Frequency Metrics for Monthly Summations of Daily Instream Flow Shortage Volumes at SB3 EF Sites in the Trinity River System (acre-feet/month)

WAM Control Point	Mean Target	Mean Shortage	Percentage of Months with Shortage Equaling or Exceeding Values Shown						
			75%	60%	50%	40%	25%	10%	Maximum
8WTGPE	2,907	272	0	5	36	105	406	1,053	2,440
8TRADE	6,600	578	0	43	106	218	631	1,242	23,293
8TROAE	29,013	773	0	0	0	142	589	3,182	8,198
8TRROE	63,822	515	0	0	0	0	382	1,135	24,522

Table 23 Frequency Metrics for Monthly Summations of Daily Instream Flow Shortage Volumes at SB3 EF Sites in the Sabine River System (acre-feet/month)

WAM Control Point	Mean Target	Mean Shortage	Percentage of Months with Shortage Equaling or Exceeding Values Shown				
			50%	40%	25%	10%	Maximum
BSBSE	2,421	29	0	0	5	116	573
SRGWE	12,056	84	0	17	87	268	1,111
SRBEE	18,922	61	0	0	40	131	1,274
29500E	2,890	122	0	0	39	436	1,722
SRRLE	62,253	2,892	0	750	2,993	9,015	57,529

Table 24 Frequency Metrics for Monthly Summations of Daily Instream Flow Shortage Volumes at SB3 EF Sites in the Neches River System (acre-feet/month)

WAM Control Point	Mean Target	Mean Shortage	Percentage of Months with Shortage Equaling or Exceeding Values Shown					
			75%	50%	40%	25%	10%	Maximum
NENEE	6,013	142	0	5	30	110	461	2,395
NEROE	19,524	211	0	0	0	288	776	2,522
ANALE	8,420	95	0	0	0	65	308	2,581
NEEVE	51,012	3,092	0	356	1,118	4,473	10,420	65,758
VIKOE	10,588	418	0	97	266	645	1,318	3,181

Table 25 Frequency Metrics for Monthly Summations of Daily Instream Flow Shortage Volumes at SB3 EF Sites in the Colorado River System (acre-feet/month)

WAM Control Point	Mean Target	Mean Shortage	Percentage of Months with Shortage Equaling or Exceeding Values Shown							
			90%	75%	60%	50%	40%	25%	10%	Maximum
B2000E	1,271	142	0	2	42	80	120	221	406	738
C3000E	883	179	0	0	24	67	136	303	518	1,288
C1000E	2,160	301	0	3	44	97	178	422	935	2,107
D4000E	2,071	242	0	14	79	153	236	383	669	1,149
D3000E	470	26	0	0	2	10	22	41	57	280
E1000E	5,873	641	0	0	80	236	438	962	1,934	6,149
F2000E	1,874	127	0	0	11	32	69	199	402	979
F1000E	17,565	1,565	0	28	296	597	1,061	2,297	4,785	15,934
G1000E	10,169	1,079	0	0	26	168	496	1,634	3,552	9,754
H1000E	4,058	538	0	0	33	108	289	711	1,604	6,472
J5000E	835	94	0	0	0	0	0	50	294	1,797
J3000E	32,842	1,404	0	0	0	23	262	1,588	4,959	19,400
J1000E	53,066	5,415	0	0	604	1,491	3,489	8,404	16,991	39,880
K2000E	52,087	10,155	0	1,107	3,076	5,302	8,322	15,314	28,792	73,107

Table 26 Frequency Metrics for Monthly Summations of Daily Instream Flow Shortage Volumes at SB3 EF Sites in the GSA River System (acre-feet/month)

WAM Control Point	Mean Target	Mean Shortage	Percentage of Months with Shortage Equaling or Exceeding Values Shown						
			90%	75%	50%	40%	25%	10%	Maximum
CP01E	4,145	209	0	0	27	80	309	700	1,905
CP02E	6,638	127	0	0	0	10	148	499	1,098
CP08E	2,632	53	0	0	0	0	46	196	722
CP10E	10,297	1,115	0	0	779	1,206	1,941	2,867	5,007
CP11E	1,003	29	0	2	18	28	48	75	184
C3846E	36,330	1,091	0	0	30	221	1,403	3,985	11,463
CP13E	930	19	0	0	5	12	27	61	197
CP14E	41,950	413	0	0	0	0	221	1,570	7,097
CP15EE	40,967	609	0	0	0	20	525	2,336	8,499
P3824E	1,913	290	0	0	17	82	369	1,001	2,999
CP28E	3,831	536	0	0	151	317	820	1,695	3,717
CP29E	14,413	7,007	723	2,434	6,867	8,596	10,541	13,930	20,729
CP32E	16,639	6,633	109	1,249	5,347	7,246	10,060	16,176	26,571
CP35E	2,143	384	0	3	199	326	634	1,080	2,573
CP37E	20,445	5,569	0	227	2,903	5,086	9,259	14,595	33,441

Table 27 Frequency Metrics for Monthly Summations of Daily Instream Flow Shortage Volumes at SB3 EF Sites in the Brazos River System (acre-feet/month)

WAM Control Point	Mean Target	Mean Shortage	Percentage of Months with Shortage Equaling or Exceeding Values Shown						
			90%	75%	50%	40%	25%	10%	Maximum
DMAS0E	436	94	0	1	45	61	117	244	922
SFAS0E	266	39	0	0	12	23	46	115	436
BRSE1E	1,604	249	0	0	29	102	353	799	2,736
CFNU1E	493	73	0	0	5	27	79	237	799
CFFG1E	1,033	287	0	4	61	153	359	1,002	2,088
BRSB2E	4,423	706	0	0	14	173	1,032	2,635	6,103
BRPP2E	7,660	1,015	0	0	253	520	1,586	3,332	6,759
BRGR3E	11,629	1,064	0	0	141	472	1,416	3,613	9,698
NBCL3E	1,142	137	0	0	5	34	152	482	1,659
BRWA4E	24,725	1,140	0	0	0	11	790	3,908	25,422
LEGT4E	1,572	292	0	0	24	61	386	959	3,213
LAKE5E	1,958	400	0	0	238	389	672	1,114	2,242
LRLR5E	10,651	2,178	0	0	1,171	1,903	3,229	5,997	15,013
LRCA5E	18,455	3,449	0	0	633	1,463	5,373	10,189	35,445
BRBR5E	74,142	10,370	0	0	1,862	4,488	114,375	34,263	106,301

Table 28 Frequency Metrics for Daily Instream Flow Shortage Volumes at SB3 EF Sites in the Trinity River System

WAM Control Point	Mean Target	Mean Shortage	Percentage of Days with Shortage Equaling or Exceeding Values Shown				
			50%	40%	25%	10%	Maximum
8WTGPE	96	9	0	0	13	35	1,681
8TRADE	217	19	0	0	14	33	7,934
8TROAE	938	25	0	0	0	139	312
8TRROE	2,107	17	0	0	0	0	1,106

Table 29 Frequency Metrics for Daily Instream Flow Shortage Volumes at SB3 EF Sites in the Sabine River System (acre-feet/day)

WAM Control Point	Mean Target	Mean Shortage	Percentage of Days with Shortage Equaling or Exceeding Values Shown				
			50%	40%	25%	10%	Maximum
BSBSE	83	1	0	0	0	0	40
SRGWE	431	3	0	0	0	0	89
SRBEE	620	2	0	0	0	0	131
29500E	95	4	0	0	0	18	56
SRRLE	2,045	95	0	0	0	417	1,882

Table 30 Frequency Metrics for Daily Instream Flow Shortage Volumes at SB3 EF Sites in the Neches River System (acre-feet/day)

WAM Control Point	Mean Target	Mean Shortage	Percentage of Days with Shortage Equaling or Exceeding Values Shown				
			50%	40%	25%	10%	Maximum
NENEE	212	5	0	0	0	9	101
NEROE	648	7	0	0	0	41	133
ANALE	266	3	0	0	0	11	109
NEEVE	1,683	102	0	0	51	451	7,597
VIKOE	355	14	0	0	0	70	165

Table 31 Frequency Metrics for Daily Instream Flow Shortage Volumes at SB3 EF Sites in the Colorado River System (acre-feet/day)

WAM Control Point	Mean Target	Mean Shortage	Percentage of Days with Shortage Equaling or Exceeding Values Shown					
			60%	50%	40%	25%	10%	Maximum
B2000E	45	5	0	0	3	8	16	24
C3000E	30	6	0	1	4	11	18	44
C1000E	72	10	0	0	0	12	40	1,918
D4000E	68	8	0	0	4	16	28	38
D3000E	18	1	0	0	0	2	2	10
E1000E	192	21	0	0	1	32	74	218
F2000E	59	4	0	0	0	6	14	391
F1000E	572	51	0	0	0	66	198	714
G1000E	330	35	0	0	0	52	130	377
H1000E	136	18	0	0	2	25	58	218
J5000E	27	3	0	0	0	0	10	67
J3000E	1,076	46	0	0	0	0	196	7,219
J1000E	1,744	178	0	0	0	240	719	2,856
K2000E	1,713	334	0	0	190	550	1,089	2,997

Table 32 Frequency Metrics for Daily Instream Flow Shortage Volumes at SB3 EF Sites in the GSA River System (acre-feet/day)

WAM Control Point	Mean Target	Mean Shortage	Percentage of Days with Shortage Equaling or Exceeding Values Shown							
			90%	75%	60%	50%	40%	25%	10%	Maximum
CP01E	139	7	0	0	0	0	0	0	35	61
CP02E	209	4	0	0	0	0	0	0	25	36
CP08E	99	2	0	0	0	0	0	0	8	26
CP10E	342	37	0	0	0	0	0	69	145	177
CP11E	35	1	0	0	0	0	0	2	4	6
C3846E	1,199	36	0	0	0	0	0	0	179	417
CP13E	49	1	0	0	0	0	0	0	2	8
CP14E	1,422	14	0	0	0	0	0	0	20	258
CP15EE	1,345	20	0	0	0	0	0	0	80	317
P3824E	66	10	0	0	0	0	0	8	38	107
CP28E	129	18	0	0	0	0	0	23	70	153
CP29E	473	230	0	22	117	192	300	389	514	726
CP32E	547	218	0	0	56	117	246	369	599	915
CP35E	73	13	0	0	0	0	5	22	42	86
CP37E	672	183	0	0	0	27	127	337	558	1,130

Table 33 Frequency Metrics for Daily Instream Flow Shortage Volumes at SB3 EF Sites in the Brazos River System (acre-feet/day)

WAM Control Point	Mean Target	Mean Shortage	Percentage of Days with Shortage Equaling or Exceeding Values Shown 50%	40%	25%	10%	Maximum
DMAS0E	14	3	0	2	4	8	30
SFAS0E	7	1	0	0	2	5	17
BRSE1E	52	8	0	0	7	32	91
CFNU1E	14	2	0	0	2	9	26
CFFG1E	32	9	0	2	10	34	67
BRSB2E	144	23	0	0	23	92	238
BRPP2E	249	33	0	0	32	131	228
BRGR3E	383	35	0	0	16	147	337
NBCL3E	33	4	0	0	2	16	65
BRWA4E	802	37	0	0	0	117	1,365
LEGT4E	54	10	0	0	6	38	107
LAKE5E	64	13	0	9	22	43	84
LRLR5E	352	72	0	45	109	220	674
LRCA5E	605	113	0	11	156	371	1,495
BRBR5E	2,438	341	0	0	365	1,286	4,872

Table 34 Percentage of Time with a Non-Zero Instream Flow Shortage in Each System

System	Percentage of Time with Non-Zero Shortage
Trinity	40%
Sabine	50%
Neches	40%
Colorado	50%
GSA	90%
Brazos	50%

Pulse flows were analyzed separately using the tracking option in the PF record. The total number of events that were initiated, terminated, and completed at each control point is summarized in Table 35 to Table 46. Pulse flows requirements in the Colorado and GSA systems have special considerations that have to be taken into account while performing the attainment analysis. The analysis for the Colorado system was subdivided for each season as small (two per season) and large (one per season). Depending on the control point, there are annual, biennial, and every 18 months' pulses in addition to seasonal pulses. Because of this, the analysis was divided into these categories of pulses (Table 38 to Table 42). A similar approach was used in the GSA system where the pulse flows are defined for each season and are divided into small, large, and periodic pulse events. Hence, the attainment analysis of was divided into these classifications of pulse events (Table 43 to Table 45).

The theoretical number off pulse flow events was computed using Equation 2, nevertheless, the theoretical number of events for the Brazos system was computed slightly differently than the other systems. The TCEQ established that the number of pulse events in the Brazos system depends on the hydrologic condition. Hence, Wurbs and Hoffpauir (2013) proposed Equation 3 to compute the theoretical number of pulses.

$$\begin{matrix} Theoretical \\ number\ of\ pulses \end{matrix} = (0.25 * \#P.dry) + (0.5 * \#P.avg) + (0.25 * \#P.wet) \qquad \textbf{Equation 3}$$

$Where,$

$\#P.dry\ =\ number\ of\ pulse\ events\ in\ the\ dry\ hydrologic\ condition$

$\#P.average\ =\ number\ of\ pulse\ events\ in\ the\ average\ hydrologic\ condition$

$\#P.wet\ =\ number\ of\ pulse\ events\ in\ the\ wet\ hydrologic\ condition$

The constants (0.25 and 0.50) are used to account for the frequency of each hydrologic condition and were defined by the final environmental flow standards as presented in Section 2.3.6.

The attainment level of flow pulses depends on the control point that is being evaluated; it can be as high as 87% (SFAS0E in the Brazos system) and as low as 8% (CP32E in the GSA system). However, it is possible to compute an attainment level for the whole basin, if all the completed and theoretical pulse events are summed (Table 47). From this analysis is possible to determine that pulse flow attainment level vary from 52% to 72% depending on the system that is being analyzed.

Table 35 Pulse Flow Summary for the Trinity River System

WAM Control Point	Summary of Pulse Flows				
	Initiated	**Terminated**	**Completed**	**Theoretical Total**	**Attainment**
8WTGPE	367	79	288	365	79%
8TRADE	347	66	281	365	77%
8TROAE	262	46	216	365	59%
8TRROE	331	104	227	365	62%
Total	1,307	295	1,012	1,460	69%

Table 36 Pulse Flow Summary for the Sabine River System

WAM Control Point	Summary of Pulse Flows				
	Initiated	**Terminated**	**Completed**	**Theoretical Total**	**Attainment**
BSBSE	379	89	290	444	65%
SRGWE	383	63	320	444	72%
SRBEE	371	80	291	444	66%
2950E	384	38	346	444	78%
SRRLE	380	22	358	444	81%
Total	1,897	292	1,605	2,220	72%

Table 37 Pulse Flow Summary for the Neches River System

WAM Control Point	Summary of Pulse Flows Initiated	Terminated	Completed	Theoretical Total	Attainment
NENEE	326	130	196	444	44%
NEROE	380	54	326	444	73%
ANALE	318	59	259	444	58%
NEEVE	341	42	299	444	67%
VIKOE	359	62	297	444	67%
Total	1,724	347	1,377	2,220	62%

Table 38 Small Pulse Flow Summary for the Colorado River System

WAM Control Point	Summary of Pulse Flows Initiated	Terminated	Completed	Theoretical Total	Attainment
B2000E	449	7	442	592	75%
C3000E	N/a	N/a	N/a	N/a	N/a
C1000E	504	21	483	592	82%
D4000E	464	9	455	592	77%
D3000E	446	21	425	592	72%
E1000E	303	1	302	444	68%
F2000E	513	24	489	592	83%
F1000E	424	5	419	592	71%
G1000E	273	6	267	444	60%
H1000E	270	5	265	444	60%
J5000E	197	0	197	296	67%
J3000E	388	0	388	592	66%
J1000E	441	0	441	592	75%
K2000E	391	0	391	592	66%
Total	5,063	99	4,964	6,956	71%

Table 39 Large Pulse Flow Summary for the Colorado River System

WAM Control Point	Summary of Pulse Flows				
	Initiated	Terminated	Completed	Theoretical Total	Attainment
B2000E	188	9	179	296	60%
C3000E	35	3	32	74	43%
C1000E	193	3	190	296	64%
D4000E	149	10	139	296	47%
D3000E	160	31	129	296	44%
E1000E	161	1	160	296	54%
F2000E	209	23	186	296	63%
F1000E	138	6	132	296	45%
G1000E	136	5	131	296	44%
H1000E	158	21	137	296	46%
J5000E	93	14	79	222	36%
J3000E	N/A	N/A	N/A	N/A	N/A
J1000E	N/A	N/A	N/A	N/A	N/A
K2000E	N/A	N/A	N/A	N/A	N/A
Total	1,620	126	1,494	2,960	50%

N/A = Not applicable.

Table 40 Annual Pulse Flow Summary for the Colorado River System

WAM Control Point	Summary of Pulse Flows				
	Initiated	Terminated	Completed	Theoretical Total	Attainment
B2000E	38	1	37	74	50%
C3000E	31	3	28	74	38%
C1000E	37	8	29	74	39%
D4000E	45	7	38	74	51%
D3000E	42	6	36	74	49%
E1000E	32	2	30	74	41%
F2000E	45	15	30	74	41%
F1000E	26	4	22	74	30%
G1000E	36	1	35	74	47%
H1000E	38	3	35	74	47%
J5000E	23	4	19	74	26%
J3000E	N/A	N/A	N/A	N/A	N/A
J1000E	N/A	N/A	N/A	N/A	N/A
K2000E	N/A	N/A	N/A	N/A	N/A
Total	393	54	339	814	42%

N/A = Not applicable.

Table 41 Colorado River System Pulse Flow Summary (every 18 months)

WAM Control Point	Summary of Pulse Flows				
	Initiated	**Terminated**	**Completed**	**Theoretical Total**	**Attainment**
B2000E	N/A	N/A	N/A	N/A	N/A
C3000E	N/A	N/A	N/A	N/A	N/A
C1000E	N/A	N/A	N/A	N/A	N/A
D4000E	N/A	N/A	N/A	N/A	N/A
D3000E	N/A	N/A	N/A	N/A	N/A
E1000E	N/A	N/A	N/A	N/A	N/A
F2000E	N/A	N/A	N/A	N/A	N/A
F1000E	N/A	N/A	N/A	N/A	N/A
G1000E	N/A	N/A	N/A	N/A	N/A
H1000E	N/A	N/A	N/A	N/A	N/A
J5000E	N/A	N/A	N/A	N/A	N/A
J3000E	33	N/A	33	49	67%
J1000E	36	N/A	36	49	74%
K2000E	36	N/A	36	49	74%
Total	105	N/A	105	148	71%

N/A = Not applicable.

Table 42 Colorado River System Pulse Flow Summary (every 2 years)

WAM Control Point	Summary of Pulse Flows				
	Initiated	**Terminated**	**Completed**	**Theoretical Total**	**Attainment**
B2000E	N/A	N/A	N/A	N/A	N/A
C3000E	N/A	N/A	N/A	N/A	N/A
C1000E	N/A	N/A	N/A	N/A	N/A
D4000E	N/A	N/A	N/A	N/A	N/A
D3000E	N/A	N/A	N/A	N/A	N/A
E1000E	N/A	N/A	N/A	N/A	N/A
F2000E	N/A	N/A	N/A	N/A	N/A
F1000E	N/A	N/A	N/A	N/A	N/A
G1000E	N/A	N/A	N/A	N/A	N/A
H1000E	N/A	N/A	N/A	N/A	N/A
J5000E	N/A	N/A	N/A	N/A	N/A
J3000E	N/A	N/A	N/A	N/A	N/A
J1000E	22	N/A	22	37	60%
K2000E	20	N/A	20	37	54%
Total	42	N/A	42	74	57%

N/A = Not applicable.

Table 43 Small Pulse Flow Summary for the GSA System

WAM Control Point	Summary of Pulse Flows				
	Initiated	Terminated	Completed	Theoretical Total	Attainment
CP01E	529	3	526	640	82%
CP02E	503	1	502	640	78%
CP08E	542	3	539	640	84%
CP10E	544	2	542	640	85%
CP11E	401	0	401	640	63%
C3846E	401	0	401	640	63%
CP13E	371	3	368	640	58%
CP14E	414	0	414	640	65%
CP15EE	395	2	393	640	61%
P3824E	503	7	496	640	78%
CP28E	498	1	497	640	78%
CP29E	175	0	175	320	55%
CP32E	137	0	137	320	43%
CP35E	149	0	149	240	62%
CP37E	161	0	161	320	50%
Total	5,723	22	5,701	8,240	69%

Table 44 Large Pulse Flow Summary for the GSA System

WAM Control Point	Summary of Pulse Flows				
	Initiated	Terminated	Completed	Theoretical Total	Attainment
CP01E	176	4	172	320	54%
CP02E	166	3	163	320	51%
CP08E	165	2	163	320	51%
CP10E	199	10	189	320	59%
CP11E	129	0	129	320	40%
C3846E	157	0	157	320	49%
CP13E	140	4	136	320	43%
CP14E	123	1	122	320	38%
CP15EE	153	0	153	320	48%
P3824E	225	15	210	320	66%
CP28E	180	8	172	320	54%
CP29E	N/A	N/A	N/A	N/A	N/A
CP32E	N/A	N/A	N/A	N/A	N/A
CP35E	N/A	N/A	N/A	N/A	N/A
CP37E	N/A	N/A	N/A	N/A	N/A
Total	1,813	47	1,766	3,520	50%

N/A = Not applicable.

Table 45 Periodic Pulse Flow Summary for GSA System

WAM Control Point	Summary of Pulse Flows				
	Initiated	Terminated	Completed	Theoretical Total	Attainment
CP01E	N/A	N/A	N/A	N/A	N/A
CP02E	N/A	N/A	N/A	N/A	N/A
CP08E	N/A	N/A	N/A	N/A	N/A
CP10E	N/A	N/A	N/A	N/A	N/A
CP11E	N/A	N/A	N/A	N/A	N/A
C3846E	N/A	N/A	N/A	N/A	N/A
CP13E	N/A	N/A	N/A	N/A	N/A
CP14E	N/A	N/A	N/A	N/A	N/A
CP15EE	N/A	N/A	N/A	N/A	N/A
P3824E	N/A	N/A	N/A	N/A	N/A
CP28E	N/A	N/A	N/A	N/A	N/A
CP29E	134	45	89	560	16%
CP32E	57	15	42	560	8%
CP35E	150	15	135	560	24%
CP37E	106	3	103	560	18%
Total	447	78	369	2,240	16%

N/A = Not applicable.

Table 46 Pulse Flow Summary for the Brazos System

WAM Control Point	Summary of Pulse Flows				
	Initiated	Terminated	Completed	Theoretical Total	Attainment
SFAS0E	203	13	190	219	87%
DMAS0E	209	22	187	219	85%
BRSE1E	206	13	193	219	88%
CFNU1E	216	30	186	237	78%
CFFG1E	200	18	182	237	77%
BRSB2E	208	12	196	219	89%
BRPP2E	473	32	441	767	58%
BRGR3E	494	45	449	767	59%
NBCL3E	195	10	185	256	72%
BRWA4E	344	26	318	493	65%
LEGT4E	334	21	313	365	86%
LAKE5E	382	60	322	493	65%
LRLR5E	377	56	321	493	65%
LRCA5E	379	106	273	493	55%
BRBR5E	423	51	372	493	75%
NAEA6E	337	40	297	365	81%
BRHE6E	467	55	412	493	84%
BRRI7E	408	47	361	493	73%
BRRO7E	405	44	361	493	73%
Total	6,260	701	5,559	7,811	71%

Table 47 Attainments of Pulse Events in Each System

System	Summary of Pulse Flows		
	Completed	Theoretical Total	Attainment
Trinity	1,012	1,460	69%
Sabine	1,605	2,220	72%
Neches	1,377	2,220	62%
Colorado	5,724	10,952	52%
GSA	7,836	14,000	56%
Brazos	5,559	7,811	71%

Additionally, Figure 14 presents the relationship between the percentage of time without instream flow shortages and the drainage area associated with each control point for the analyzed river systems.

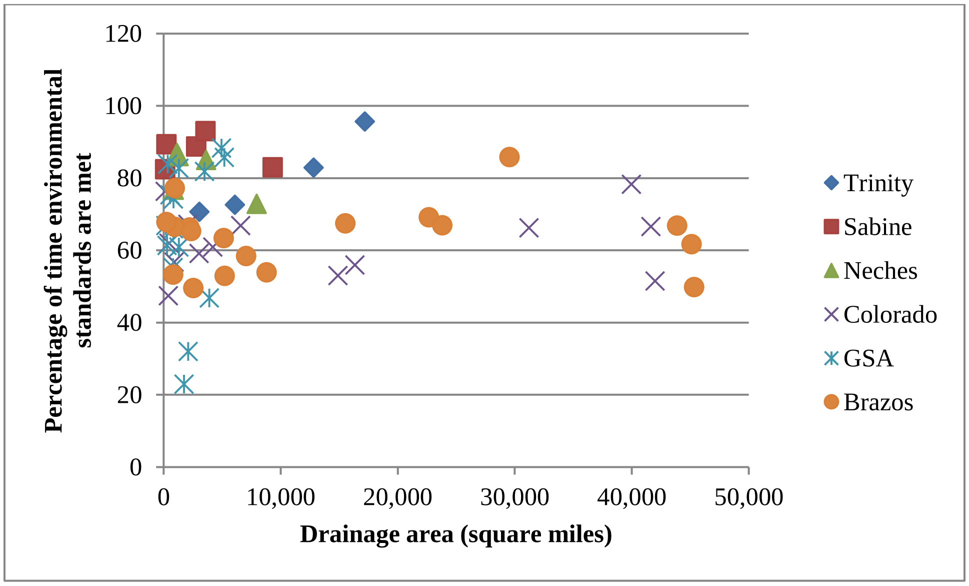

Figure 14 Percentage of Time Without Instream Flow Shortages and Drainage Area at EF Control Points

5. TARGETS FROM DAILY SIMULATIONS INTO MONTHLY MODELS

The WAMs for three river systems (Trinity, Sabine, and Neches) were selected as case studies to analyze the validity of the proposed methodology described in Section 3.3; which incorporates monthly summations of daily targets for SB3 environmental flow standards computed in a daily SIMD simulation as input to a monthly SIM simulation. Input data modeling the SB3 flow standards in the monthly WAMs are removed and replaced with the monthly targets generated with daily WAMs. Frequency metrics for the monthly instream flow targets and corresponding monthly shortages from the monthly simulation results are compared to the daily simulation monthly summation frequency metrics presented in the preceding section.

Wurbs and Hoffpauir (2013) originally developed the strategy of providing monthly summations of daily targets computed in a daily simulation as input to a monthly simulation. Applications of this modeling strategy with the daily WAMs are described by the technical reports available at the WRAP website discussed in Section 3. Datasets of monthly SB3 environmental flow standard targets created with the six daily WAMs are included in the WAM datasets available at the WRAP website.

The WAM simulation studies presented in Section 4, 5, and 6 employ the previously developed daily WAMs. Section 5 focuses specifically on exploring this previously proposed strategy for combining the much more complex daily WAMs with the routinely applied monthly WAMs to integrate SB3 environmental flow standards in the WAM system. The accuracy of the combined daily/monthly modeling approach is assessed and key issues associated with the approach are identified and discussed.

After implementing the proposed methodology, the water rights and control points (Table 16 to Table 18), relevant to this study, were identified; the shortage-frequency analysis was performed for the SB3 environmental flow standards monthly shortage volumes (Table 48 to Table 50). The shortage-frequency metrics performed for the Trinity, Sabine, and Neches WAMs were done considering a hydrologic period of analysis of 1940-2013 (888 months).

Table 48 Frequency Metrics for Monthly Instream Flow Shortage Volumes at SB3 EF Sites in the Trinity River System (acre-feet/month)

Control Point	Mean Target	Mean shortage	Percentage of Months with Shortage Equaling or Exceeding Values Shown					
			60%	50%	40%	25%	10%	Maximum
8WTGPE	2,907	330	0	0	0	511	1,294	3,930
8TRADE	6,600	4,919	0	910	6,895	10,813	12,907	36,330
8TROAE	29,013	25,141	0	5,325	23,325	40,211	75,509	208,157
8TRROE	63,822	14,791	0	1,268	14,637	29,142	42,804	190,780

Table 49 Frequency Metrics for Monthly Instream Flow Shortage Volumes at SB3 EF Sites in the Sabine River System (acre-feet/month)

WAM Control Point	Mean Target	Mean Shortage	Percentage of Months with Shortage Equaling or Exceeding Values Shown				
			50%	40%	25%	10%	Maximum
BSBSE	2,421	18	0	0	0	0	771
SRGWE	12,056	184	0	0	0	28	20,660
SRBEE	18,922	372	0	0	0	0	81,709
29500E	2,890	75	0	0	0	83	1,722
SRRLE	62,253	958	0	0	0	0	72,042

Table 50 Frequency Metrics for Monthly Instream Flow Shortage Volumes at SB3 EF Sites in the Neches River System (acre-feet/month)

WAM Control Point	Mean Target	Mean Shortage	Percentage of Months with Shortage Equaling or Exceeding Values Shown				
			50%	40%	25%	10%	Maximum
NENEE	6,013	383	0	0	221	1,634	9,364
NEROE	19,524	111	0	0	0	0	15,148
ANALE	8,420	72	0	0	0	0	6,796
NEEVE	51,012	2,994	0	0	3,695	11,398	129,599
VIKOE	10,588	50	0	0	0	0	2,713

Because of how the proposed methodology works, the mean targets in the monthly and daily simulation are the same. Nevertheless, the frequency and magnitude of the instream flow shortage volumes vary greatly in comparison to the results obtained through the daily simulation presented in Section 4. This can be seen in Table 51 where the maximum shortages computed for each control point are presented for the two methodologies. All the maximum instream flow shortages computed with the proposed methodology are greater than or equal to the results presented in Section 4.

The percentage of time with a non-zero shortage at the three systems was also compared to the results obtained for the monthly summations of daily instream flow shortage volumes presented in Section 4. This comparison is presented in Table 52 and reveals that in the proposed methodology the occurrence of shortages is lower compared to the daily simulation. The greatest reduction occurs in the Sabine system where the percentage of months with a non-zero shortage is reduced from 40% to 10%.

Table 51 Comparison of Maximum Instream Flow Shortage Volumes at SB3 EF Sites (acre-feet/month)

System	WAM Control Point	Maximum Shortage Monthly Simulation	Maximum Shortage Daily Simulation*
Trinity	8WTGPE	3,930	2,440
	8TRADE	36,330	23,293
	8TROAE	208,157	8,198
	8TRROE	190,780	24,522
Sabine	BSBSE	771	573
	SRGWE	20,660	1,111
	SRBEE	81,709	1,274
	29500E	1,722	1,722
	SRRLE	72,042	57,529
Neches	NENEE	9,364	2,395
	NEROE	15,148	2,522
	ANALE	6,796	2,581
	NEEVE	129,599	65,758
	VIKOE	2,713	3,181

*Values computed for monthly summations of daily regulated flow volumes.

Table 52 Percentage of Time with a Non-Zero Instream Flow Shortage in Each System

System	Daily Simulation*	Monthly Simulation
Trinity	60%	50%
Sabine	40%	10%
Neches	50%	25%

*Values computed for monthly summations of daily instream flow shortage volumes.

Considering that in the proposed methodology instream flow shortages are less frequent, it is important to compare the regulated flows at the control points where environmental flow standards are defined. A flow frequency analysis for regulated flows in the three systems is presented in Table 53 to Table 55. Based on these tables, it is possible to conclude that regulated flows computed using the daily model tend to be greater than or equal to the flows computed using the monthly model. Therefore, the percentage of time with a zero regulated flows is greater in the monthly model. Despite these discrepancies, the mean regulated flows computed with both methodologies are very similar. The maximum percentage difference for each case study is 1%, 3%, and 10% for the Sabine, Neches, and Trinity, respectively (Table 56)

Table 53 Frequency Metrics for Monthly Regulated Flow Volumes at SB3 EF Sites in the Trinity River System (acre-feet/month)

	Monthly Simulation				Daily Simulation*			
Control Point	**8WTGPE**	**8TRDAE**	**8TROAE**	**8TRROE**	**8WTGPE**	**8TRDAE**	**8TROAE**	**8TRROE**
Mean	24,399	47,528	192,382	319,604	27,162	52,904	199,365	323,423
Minimum	0	0	0	1	177	129	179	272
99.50%	0	0	0	5,873	180	177	181	20,287
99%	0	0	0	14,691	186	186	194	30,578
98%	0	0	0	26,201	188	189	246	44,205
95%	0	0	1	42,392	238	238	308	58,976
90%	0	1	2,807	59,960	317	316	5,307	66,189
85%	213	553	8,694	65,357	337	863	11,406	72,248
80%	741	1,240	13,435	69,980	1,386	2,674	16,172	79,395
75%	1,193	2,223	18,282	76,879	2,421	4,355	23,493	88,150
70%	2,008	3,207	23,459	87,818	3,570	6,299	30,982	97,003
60%	3,491	6,539	37,984	107,407	5,529	12,214	52,375	114,810
50%	5,297	12,862	62,508	129,249	9,288	19,923	86,821	138,095
40%	8,354	20,288	97,820	155,660	13,550	32,273	127,790	163,096
30%	13,324	30,990	148,740	247,811	20,746	44,242	190,182	270,127
25%	17,113	38,347	203,792	327,100	26,662	58,003	253,408	373,377
20%	23,223	48,544	267,689	471,181	36,720	72,654	320,129	536,833
15%	35,036	76,268	374,510	659,831	47,139	99,182	419,986	692,088
10%	64,791	119,855	521,945	910,740	66,006	138,839	526,168	925,364
5%	112,443	205,241	859,201	1,259,460	103,195	209,891	782,491	1,147,734
2%	214,235	385,417	1,494,270	1,911,537	202,922	379,061	1,302,835	1,628,032
1%	340,893	724,759	1,808,881	2,335,625	334,856	540,163	1,500,963	2,041,688
0.50%	466,116	945,820	2,207,449	2,718,158	429,360	627,260	1,681,467	2,362,523
Maximum	716,124	1,170,380	2,804,964	3,505,024	608,612	1,049,429	2,109,249	3,140,498

*Values computed for monthly summations of daily regulated flow volumes.

Table 54 Frequency Metrics for Monthly Regulated Flow Volumes at SB3 EF Sites in the Sabine River System (acre-feet/month)

	Monthly Simulation					Daily Simulation*				
Control Point	**SRRLE**	**BSBSE**	**SRGWE**	**SRBEE**	**29500E**	**SRRLE**	**BSBSE**	**SRGWE**	**SRBEE**	**29500E**
Mean	338,065	10,921	81,644	114,009	11,646	334,831	10,926	84,515	117,020	11,646
Minimum	3,381	134	0	0	0	823	134	0	49	0
99.50%	8,626	416	0	0	0	3,003	412	0	196	0
99%	13,321	488	0	155	0	6,135	488	9	297	0
98%	16,218	567	0	472	0	8,674	566	126	676	0
95%	25,613	801	545	1,695	760	14,776	926	712	2,618	760
90%	39,176	1,142	1,796	3,538	1,328	25,047	1,404	2,955	5,145	1,328
85%	53,489	1,435	3,828	5,916	1,987	34,723	1,636	5,384	8,037	1,987
80%	73,044	1,755	5,473	9,361	2,654	45,274	1,947	7,827	11,291	2,654
75%	89,468	2,307	8,623	12,543	3,373	52,894	2,420	10,303	15,330	3,373
70%	112,782	2,797	10,982	15,703	4,136	62,732	2,831	13,860	20,451	4,136
60%	146,818	3,987	19,879	29,707	5,777	96,667	3,927	25,431	36,855	5,777
50%	172,798	5,815	31,727	49,610	7,923	139,120	5,736	39,319	59,828	7,923
40%	222,762	8,381	53,340	81,481	10,332	207,978	8,326	61,883	89,477	10,332
30%	314,322	12,422	77,141	116,416	13,831	346,959	12,277	88,866	129,011	13,831
25%	416,334	14,961	94,046	139,907	16,310	442,846	14,806	109,665	151,039	16,310
20%	504,609	18,638	118,476	184,543	19,228	597,459	18,640	131,618	197,358	19,228
15%	693,888	23,967	155,050	242,788	22,581	757,308	23,970	165,902	254,887	22,581
10%	905,764	28,723	215,968	321,117	27,450	963,401	28,184	220,777	317,928	27,450
5%	1,243,742	37,520	350,379	455,243	35,594	1,249,988	37,487	337,039	432,884	35,594
2%	1,635,066	48,136	525,822	618,071	46,434	1,644,589	48,124	476,717	561,720	46,434
1%	2,114,672	54,305	594,131	748,383	54,029	2,103,854	54,206	571,722	688,326	54,029
0.50%	2,546,593	62,109	776,610	988,465	70,125	2,514,464	62,108	671,796	887,185	70,125
Maximum	3,644,227	108,251	1,359,388	1,699,673	83,445	3,634,038	108,246	1,362,043	1704,412	83,445

*Values computed for monthly summations of daily regulated flow volumes.

Table 55 Frequency Metrics for Monthly Regulated Flow Volumes at SB3 EF Sites in the Neches River System (acre-feet/month)

	Monthly Simulation					Daily Simulation*				
Control Point	**NENEE**	**NEROE**	**ANALE**	**NEEVE**	**VIKOE**	**NENEE**	**NEROE**	**ANALE**	**NEEVE**	**VIKOE**
Mean	24,754	122,300	43,034	260,401	53,195	25,019	122,395	43,215	259,069	53,194
Minimum	0	0	0	0	830	0	0	0	0	829
99.50%	565	0	0	0	1,539	412	0	0	2	1,539
99%	1,614	0	0	0	1,700	1,238	0	0	7	1,693
98%	1,926	0	0	4	2,032	1,745	19	157	12	2,029
95%	2,193	978	496	2,081	3,185	2,244	1,238	714	29	3,175
90%	2,465	2,795	1,367	4,705	4,442	2,625	3,180	1,509	4,917	4,432
85%	2,708	5,515	2,271	7,687	6,702	3,004	6,387	2,362	8,740	6,695
80%	3,069	8,290	3,092	10,347	8,088	3,097	9,392	3,518	14,918	8,083
75%	3,123	11,009	4,389	14,833	10,297	3,547	11,881	4,939	19,936	10,306
70%	3,329	15,066	5,698	20,752	12,977	4,380	17,206	6,245	26,851	12,947
60%	5,576	27,495	9,582	38,029	17,994	6,544	28,938	11,333	44,116	18,007
50%	7,990	52,106	16,169	60,095	28,013	9,191	55,215	17,384	72,069	28,007
40%	12,670	84,230	26,136	124,139	39,520	14,238	84,591	27,004	141,452	39,523
30%	21,020	132,811	45,768	284,432	57,405	23,059	137,060	46,667	281,722	57,411
25%	27,409	172,586	59,522	398,315	73,613	29,268	174,267	60,552	384,113	73,613
20%	36,117	213,524	79,320	506,243	87,350	37,423	216,335	80,352	472,469	87,349
15%	46,635	283,842	102,460	643,064	108,024	46,312	276,901	100,227	652,145	108,032
10%	70,941	354,477	125,242	800,443	130,075	64,739	348,868	125,946	795,974	130,076
5%	114,560	458,750	172,158	1,104,187	198,888	110,355	440,170	167,930	1,065,491	198,890
2%	155,270	631,484	221,928	1,397,932	254,882	144,386	636,445	212,702	1,413,748	254,898
1%	184,030	773,934	252,020	1,802,531	305,249	173,576	773,675	252,019	1,595,916	305,284
0.50%	234,587	874,940	302,772	2,007,291	389,969	235,701	884,484	292,133	1,670,510	389,986
Maximum	399,228	1,455,300	451,793	3,004,787	437,579	400,404	1,448,355	450,369	1,910,771	437,598

*Values computed for monthly summations of daily regulated flow volumes.

Table 56 Monthly Mean Regulated Flow Volumes Comparison at SB3 EF Sites (acre-feet/month)

System	Control Point	Mean Regulated Flow (Monthly Simulation)	Mean Regulated Flow (Daily Simulation*)	Difference
Sabine	SRRLE	338,065	334,831	1%
	BSBSE	10,921	10,926	0%
	SRGWE	81,644	84,515	3%
	SRBEE	114,009	117,020	3%
	29500E	11,646	11,646	0%
Neches	NENEE	24,754	25,019	1%
	NEROE	122,300	122,395	0%
	ANALE	43,034	43,215	0%
	NEEVE	260,401	259,069	1%
	VIKOE	53,195	53,194	0%
Trinity	8WTGPE	24,399	27,162	10%
	8TRDAE	47,528	52,904	10%
	8TROAE	192,382	199,365	4%
	8TRROE	319,604	323,423	1%

*Values computed for monthly summations of daily regulated flow volumes.

6. IMPACT OF ENVIRONMENTAL FLOW STANDARDS ON WATER AVAILABILITY

The effective priority date of the SB3 environmental flow standards varies between the river systems from December 2009 to September 2012. The SB3 flow standards are treated in the water rights system as being junior to all the water rights previously adjudicated or permitted with earlier priority dates. Therefore, most of the water rights in the analyzed river systems can curtail the environmental flow standards, which explains the instream flow shortages presented in the simulation results in the previous section. Consequently, only future water rights are affected by the implementation of environmental flow standards; thus, water availability should not be analyzed in terms of the reliability of old water rights but on the effect that environmental flow standards have on the unappropriated water.

The best metric available to measure the impact of SB3 standards is a flow frequency analysis for unappropriated flows at the control points where the standards were defined by TCEQ. Two simulations were required for each river system: (a) a simulation including all the environmental flow standards (the simulations presented in Section 4.1) and (b) a simulation that did not include environmental flow standards. The following paragraphs present the results of the flow frequency analysis for unappropriated flows in the 12 simulations.

The flow frequency analyses, including and not including SB3 environmental flow standards (Table 57 to Table 69), were performed using the same approach described in Section 4. Unappropriated flows were used instead of instream flow shortages. As expected, daily unappropriated flows frequency and magnitude decrease once SB3 environmental flow standards are included in the simulation, because old water rights are not curtailed by the newly implemented standards. The frequency analysis reveals that frequency and magnitude of unappropriated flows change depending not only on the system but the control point that is being analyzed. Hence, these analyses have been used to determine the percentage of time with non-zero unappropriated flows for all case studies). The percentage of time with water available for new water rights ranges from 30% to 0.5% and 25% to 0.5% for the simulations with and without including SB3 environmental flow standards, respectively. Based on the information presented in Table 70, it is evident that the Colorado is the most critical case.

Besides the geographical variation, one of the main conclusions drawn from the frequency analysis is that acquiring new water rights has become tougher due to the seniority system implemented in the state, unless old water rights are revoked, modified, or curtailed. The Colorado and Brazos systems are the most critical cases considering that they count with the lowest frequency and mean magnitude of unappropriated.

Table 57 Frequency Metrics for Daily Unappropriated Flow Volumes at SB3 EF Sites in the Trinity System (acre-feet/day)

Control Point	Without Including SB3 Standards				Including SB3 Standards			
	8WTGPE	8TRDAE	8TROAE	8TRROE	8WTGPE	8TRDAE	8TROAE	8TRROE
Mean	288	598	4,167	7,931	258	525	3,586	7,260
50%	0	0	0	0	0	0	0	0
40%	0	0	33	10	0	0	0	0
30%	0	0	1,637	3,545	0	0	556	2,482
25%	0	0	3,098	6,529	0	0	1,744	5,089
20%	0	0	5,069	11,099	0	0	3,421	8,984
15%	0	85	8,177	17,454	0	0	6,050	14,785
10%	154	1,030	13,070	26,610	22	633	10,931	24,420
5%	1,416	3,338	23,518	42,782	1,127	2,727	21,794	40,439
2%	3,555	8,157	37,404	68,683	3,166	7,356	35,867	66,639
1%	6,159	13,161	47,603	91,147	5,704	12,581	46,711	89,821
0.50%	10,327	18,165	67,361	109,475	10,136	17,902	65,902	108,264
Maximum	59,879	75,316	169,526	300,874	59,879	75,227	168,634	299,625

Table 58 Frequency Metrics for Daily Unappropriated Flow Volumes at SB3 EF Sites in the Sabine System (acre-feet/day)

	Without Including SB3 Standards					Including SB3 Standards				
Control Point	**BSBSE**	**SRGWE**	**SRBEE**	**29500E**	**SRRLE**	**BSBSE**	**SRGWE**	**SRBEE**	**29500E**	**SRRLE**
Mean	123	1,386	2,095	348	5,474	97	1,202	1,834	262	5,223
95%	0	0	0	0	0	0	0	0	0	0
90%	0	0	0	0	18	0	0	0	0	0
85%	0	0	0	0	112	0	0	0	0	0
80%	0	0	0	10	241	0	0	0	0	29
75%	0	0	0	30	401	0	0	0	0	158
70%	0	0	0	51	579	0	0	0	0	307
60%	0	0	0	99	1,085	0	0	0	18	673
50%	0	0	0	156	1,788	0	0	0	55	1,314
40%	0	0	0	228	2,951	0	0	0	118	2,474
30%	0	0	0	330	5,052	0	0	0	212	4,698
25%	60	644	1,055	398	6,610	0	87	250	277	6,344
20%	157	1,658	2,866	490	8,852	51	879	1,773	363	8,715
15%	271	2,965	4,893	611	12,245	157	2,114	3,792	469	12,089
10%	427	4,737	7,800	819	16,174	320	4,029	6,769	666	16,030
5%	711	7,913	12,469	1,257	22,979	611	7,307	11,435	1,077	22,797
2%	1,132	12,846	18,331	2,053	32,843	1,048	12,402	17,528	1,836	32,831
1%	1,471	17,488	22,948	2,878	40,650	1,402	16,961	22,490	2,622	40,645
0.50%	1,880	22,823	28,249	4,153	48,871	1,836	22,251	27,701	3,896	48,823
Maximum	6,712	84,596	99,440	31,932	164,417	6,317	84,596	99,440	31,809	164,417

Table 59 Frequency Metrics for Daily Unappropriated Flow Volumes at SB3 EF Sites in the Neches System (acre-feet/day)

Control Point	Without Including SB3 Standards					Including SB3 Standards				
	NENEE	NEROE	ANALE	NEEVE	VIKOE	NENEE	NEROE	ANALE	NEEVE	VIKOE
Mean	469	3,108	952	7,009	1,455	385	2,550	808	6,036	1,194
70%	0	0	0	0	0	0	0	0	0	0
60%	0	0	0	0	32	0	0	0	0	0
50%	0	0	0	628	233	0	0	0	161	49
40%	0	989	0	2,233	587	0	119	0	1,143	247
30%	100	2,864	195	5,958	1,150	0	1,606	3.6	3,338	698
25%	253	3,999	606	8,625	1,574	61	2,650	264	5,877	1,051
20%	448	5,530	1,123	11,864	2,159	175	4,152	680	9,313	1,575
15%	736	7,492	1,865	16,346	2,998	388	6,189	1,341	14,053	2,324
10%	1,265	10,360	3,089	24,641	4,368	892	9,071	2,471	22,437	3,626
5%	2,685	15,185	5,513	36,097	7,191	2,355	13,777	4,921	33,714	6,522
2%	5,000	21,237	9,431	48,439	10,453	4,782	19,582	8,927	46,275	9,951
1%	7,156	26,092	12,047	54,328	13,470	7,034	24,141	11,624	51,908	13,135
0.50%	9,035	30,692	15,423	59,066	17,404	8,858	28,365	15,102	56,828	17,105
Maximum	40,738	61,035	34,801	183,371	57,744	40,548	60,202	34,623	183,371	57,550

Table 60 Frequency Metrics for Daily Unappropriated Flow Volumes at SB3 EF Sites in the GSA System (acre-feet/day)

	Without Including SB3 Standards					Including SB3 Standards				
Control Point	**CP01E**	**CP02E**	**CP08**	**CP10E**	**CP11E**	**CP01E**	**CP02E**	**CP08**	**CP10E**	**CP11E**
Mean	45	76	115	341	95	30	51	88	210	74
30%	0	0	0	0	0	0	0	0	0	0
25%	0	0	0	115	4	0	0	0	0	0
20%	0	0	0	355	17	0	0	0	45	1.2
15%	0	0	89	673	50	0	0	0	171	11
10%	0	0	308	1,100	142	0	0	153	458	72
5%	143	306	703	1,797	455	0	8.3	534	1,060	294
2%	831	1,332	1,323	3,255	1,186	529	926	1,147	2,531	914
1%	1,264	2,171	2,022	4,771	1,919	1,002	1,382	1,760	4,056	1,694
0.50%	1,631	2,771	2,833	6,270	3,156	1,311	2,154	2,574	5,947	2,961
Maximum	15,510	14,970	20,517	40,411	20,510	15,510	14,970	20,517	40,411	20,510

Table 61 Frequency Metrics for Daily Unappropriated Flow Volumes at SB3 EF Sites in the GSA System (acre-feet/day)

	Without Including SB3 Standards					Including SB3 Standards				
Control Point	**C3846E**	**CP13E**	**CP14**	**CP15EE**	**P3824E**	**C3846E**	**CP13E**	**CP14**	**CP15EE**	**P3824E**
Mean	1,191	220	2,062	2,867	13	781	179	1,571	1,767	9
99.5%	0	0	0	0	0	0	0	0	0	0
99%	0	0	0	0	0	0	0	0	0	0
95%	0	0	0	0.9	0	0	0	0	0	0
90%	0	0	0	31	0	0	0	0	0	0
85%	0	0	0	99	0	0	0	0	0	0
80%	0	0	0	201	0	0	0	0	0	0
75%	0	0	0	318	0	0	0	0	47	0
70%	0	0	0	441	0	0	0	0	101	0
60%	0	0	0	599	0	0	0	0	155	0
50%	0	0	0	1,507	0	0	0	0	315	0
40%	0	4.5	241	2,083	0	0	0	40	571	0
30%	77	15	726	2,459	0	8.6	1.8	204	757	0
25%	333	39	1,156	2,567	0	102	10	416	953	0
20%	785	62	1,626	2,708	0	159	28	570	1,074	0
15%	1,434	103	2,293	3,083	0	244	57	740	1,346	0
10%	1,793	177	3,180	3,682	0	470	110	1,238	1,954	0
5%	3,191	359	5,808	6,372	0	1,209	227	4,394	4,418	0
2%	8,581	938	10,658	10,819	0	6,251	647	9,840	9,301	0
1%	11,935	2,386	17,232	15,770	106	10,497	1,965	16,136	14,729	0
0.50%	12,436	4,382	23,653	22,431	403	11,414	3,915	22,989	21,293	257
Maximum	14,757	6,677	32,627	30,831	612	13,225	6,355	32,447	30,450	498

Table 62 Frequency Metrics for Daily Unappropriated Flow Volumes at SB3 EF Sites in the GSA System (acre-feet/day)

Control Point	Without Including SB3 Standards				Including SB3 Standards			
	CP28E	CP29E	CP32	CP35E	CP28E	CP29E	CP32	CP35E
Mean	288	598	4,167	7,931	258	525	3,586	7,260
60%	120	195	251	165	81	115	175	132
50%	0	0	0	0	0	0	0	0
40%	0	0	0	13	0	0	0	0
30%	0	0	0	35	0	0	0	0
25%	0	0	0	68	0	0	0	4.8
20%	0	0	0.8	95	0	0	0	37
15%	0	64	77	137	0	0	0	81
10%	46	203	224	213	0	0	18	152
5%	206	447	518	353	0	49	253	288
2%	539	927	1,234	722	281	476	854	620
1%	1,245	2,015	2,960	1,528	944	1,369	2,210	1,311
0.50%	2,262	3,509	4,935	2,675	1,703	2,546	3,782	2,344
Maximum	3,964	6,010	7,211	4,259	3,002	4,293	5,753	3,816

Table 63 Frequency Metrics for Daily Unappropriated Flow Volumes at SB3 EF Sites in the Colorado System (acre-feet/day)

	Without Including SB3 Standards					Including SB3 Standards				
Control Point	**B2000E**	**C3000E**	**C1000E**	**D4000E**	**D3000E**	**B2000E**	**C3000E**	**C1000E**	**D4000E**	**D3000E**
Mean	1.5	0	3.0	8.7	2.8	1.1	0	2.3	7.5	2.4
5%	0	0	0	0	0	0	0	0	0	0
2%	0	0	0	6.3	0	0	0	0	0	0
1%	14	0	34	79	28	0	0	2.9	33	16
0.50%	36	0	87	184	75	25	0	61	143	63
Maximum	4,148	537	7,927	44,031	12,059	4,148	230	7,869	4,4031	12,057

Table 64 Frequency Metrics for Daily Unappropriated Flow Volumes at SB3 EF Sites in the Colorado System (acre-feet/day)

	Without Including SB3 Standards					Including SB3 Standards				
Control Point	**E1000E**	**F2000E**	**F1000E**	**G1000E**	**H1000E**	**E1000E**	**F2000E**	**F1000E**	**G1000E**	**H1000E**
Mean	40	60	191	99	58	30	53	152	74	47
10%	0	0	0	0	0	0	0	0	0	0
5%	0	0	0	0	0	0	0	0	0	0
2%	544	347	1,721	1,232	730	352	204	991	827	564
1%	903	1,108	4,089	2,100	1,414	679	911	3,476	1,638	1,193
0.50%	1,600	2,688	8,896	3,625	2,412	1,214	2,408	7,349	2,946	2,077
Maximum	27,811	41,585	96,619	87,868	31,567	27,811	37,621	96,202	87,868	31,567

Table 65 Frequency Metrics for Daily Unappropriated Flow Volumes at SB3 EF Sites in the Colorado System (acre-feet/day)

	Without Including SB3 Standards				Including SB3 Standards			
Control Point	J5000E	J3000E	J1000E	K2000E	J5000E	J3000E	J1000E	K2000E
Mean	22	704	948	995	17	592	788	854
10%	0	0	0	0	0	0	0	0
5%	63	2,118	2,356	2,439	5.5	934	1,124	1,405
2%	273	9,057	12,220	12,942	211	7,473	9,768	10,914
1%	514	17,115	27,238	30,658	443	15,525	23,173	26,911
0.50%	797	39,035	51,765	56,078	706	35,190	47,098	50,719
Maximum	10,038	92,647	152,369	146,744	8,580	83,177	137,222	145,228

Table 66 Frequency Metrics for Daily Unappropriated Flow Volumes at SB3 EF Sites in the Brazos System (acre-feet/day)

	Without Including SB3 Standards					Including SB3 Standards				
Control Point	SFAS0E	DMAS0E	BRSE1E	CFNU1E	CFFG1E	SFAS0E	DMAS0E	BRSE1E	CFNU1E	CFFG1E
Mean	43	35	144	32	91	36	30	114	29	81
10%	0	0	0	0	0	0	0	0	0	0
5%	24	7.7	132	0	0.9	0	0	0	0	0
2%	284	244	1,498	132	698	166	141	894	54	381
1%	848	705	3,221	439	1,938	630	540	2,535	329	1,443
0.50%	1,818	1,714	6,287	1,022	4,467	1,576	1,547	5,517	838	3,877
Maximum	32,402	25,440	81,851	38,231	33,029	32,227	25,436	76,476	38,225	32,962

Table 67 Frequency Metrics for Daily Unappropriated Flow Volumes at SB3 EF Sites in the Brazos System (acre-feet/day)

	Without Including SB3 Standards					Including SB3 Standards				
Control Point	**BRSB2E**	**BRPP2E**	**BRGR3E**	**NBCL3E**	**BRWA4E**	**BRSB2E**	**BRPP2E**	**BRGR3E**	**NBCL3E**	**BRWA4E**
Mean	322	337	517	168	1,970	269	266	400	141	1,512
40%	0	0	0	0	0	0	0	0	0	0
30%	0	0	0	0	622	0	0	0	0	0
25%	0	0	0	0	918	0	0	0	0	0
20%	0	0	0	0	1,317	0	0	0	0	222
15%	0	0	0	0	2,093	0	0	0	0	940
10%	0	0	0	295	3,936	0	0	0	91	2,415
5%	492	777	1,585	829	9,994	0	0	435	680	7,754
2%	2,898	3,522	6,434	1,938	25,812	2,067	2,444	4,749	1,704	22,339
1%	7,963	8,235	13,364	3,172	37,784	6,037	6,231	9,890	2,920	36,061
0.50%	17,397	17,673	24,048	6,219	48,193	15,836	15,605	19,717	5,727	46,596
Maximum	114,361	100,353	144,090	23,522	132,407	112,803	100,287	144,016	23,488	131,992

Table 68 Frequency Metrics for Daily Unappropriated Flow Volumes at SB3 EF Sites in the Brazos System (acre-feet/day)

	Without Including SB3 Standards					Including SB3 Standards				
Control Point	**LEGT4E**	**LAKE5E**	**LRLR5E**	**LRCA5E**	**BRBR5E**	**LEGT4E**	**LAKE5E**	**LRLR5E**	**LRCA5E**	**BRBR5E**
Mean	292	109	944	2,069	6,328	248	84	753	1630	4,899
50%	0	0	0	0	0	0	0	0	0	0
40%	0	0	0	8.0	1,000	0	0	0	0	0
30%	0	0	0	541	2,929	0	0	0	0	0
25%	0	0	162	1,049	4,539	0	0	0	0	1,053
20%	0	0	555	2,030	7,299	0	0	0	560	3,300
15%	172	81	1,362	3,937	11,990	0	0	398	2,200	7,798
10%	594	322	3,015	7,181	20,042	291	115	1,939	5,662	15,603
5%	1,584	754	5,950	13,328	34,756	1,350	624	5,482	12,201	29,813
2%	4,182	1,313	11,460	19,835	61,575	3,936	1,198	11,034	18,328	57,381
1%	6,117	1,809	13,238	19,835	79,232	5,942	1,665	12,712	19,220	75,140
0.50%	7,702	2,353	15,780	22,210	95,285	7,464	2,203	15,441	20,988	91,721
Maximum	60,870	10,615	52,967	100,674	312,717	60,824	10,304	52,460	100,258	309,241

Table 69 Frequency Metrics for Daily Unappropriated Flow Volumes at SB3 EF Sites in the Brazos System (acre-feet/day)

Control Point	Without Including SB3 Standards NAEA6E	BRHE6E	BRRI7E	BRRO7E	Including SB3 Standards NAEA6E	BRHE6E	BRRI7E	BRRO7E
Mean	335	8,890	11,131	10,797	301	6,740	8,009	8,112
80%	0	0	0	0	0	0	0	0
75%	0	0	0	0.6	0	0	0	0
70%	0	0	12	119	0	0	0	0
60%	0	0	999	694	0	0	0	0
50%	0	0	2,710	1,895	0	0	0	0
40%	0	2,408	5,391	4,112	0	0	125	473
30%	0	5,857	9,281	8,095	0	1,200	3,468	3,403
25%	0	8,699	12,357	11,042	0	3,793	6,150	5,838
20%	32	13,013	16,383	15,254	0	7,474	10,069	9,568
15%	112	19,158	22,685	21,657	32	13,250	16,043	15,476
10%	406	27,981	32,393	32,217	250	22,103	25,681	25,426
5%	1,802	46,667	52,474	53,975	1,480	40,048	45,918	47,429
2%	4,777	75,713	84,347	85,148	4,458	70,414	77,757	78,845
1%	7,514	96,262	106,225	106,982	7,353	90,096	100,486	99,574
0.50%	10,638	110,388	118,468	120,660	10,491	104,853	111,116	114,943
Maximum	40,009	282,669	515,435	803,636	40,009	282,526	512,117	799,395

Table 70 Percentage of Time with Non-Zero Unappropriated Flows in Each System

System	Without Including SB3 Standards	Including SB3 Standards
Trinity	10%	10%
Sabine	25%	20%
Neches	30%	25%
Colorado	0.5%	0.5%
GSA	5%	2%
Brazos	5%	2%

As mentioned before, SB3 environmental flow standards attainment and unappropriated flow volumes change depending on the control point that is being analyzed. However, it is possible to recognize a trend in the results obtained while identifying the location of the SB3 sites in each of the systems (Figure 15 to Figure 20); the magnitude of unappropriated flow increases from upstream to downstream in all the case studies. This becomes evident only if the SB3 EF sites located in the main stem of the systems are analyzed. Consequently, instream flow shortage volumes decrease from upstream to downstream, although the SB3 instream flow mean target increases. This relationship occurs because the catchment area of the river increases from upstream to downstream favoring the attainment of SB3 environmental flow standards in the control points located near to the outlet of the watershed. It is cogent to conclude that obtaining new water rights at locations closer to the outlet of the systems is more feasible compared to the headwaters.

Although the daily instream flow shortages volumes decrease from upstream to downstream, the attainment level of pulse flow events does not follow a consistent trend that is applicable to all the case studies.

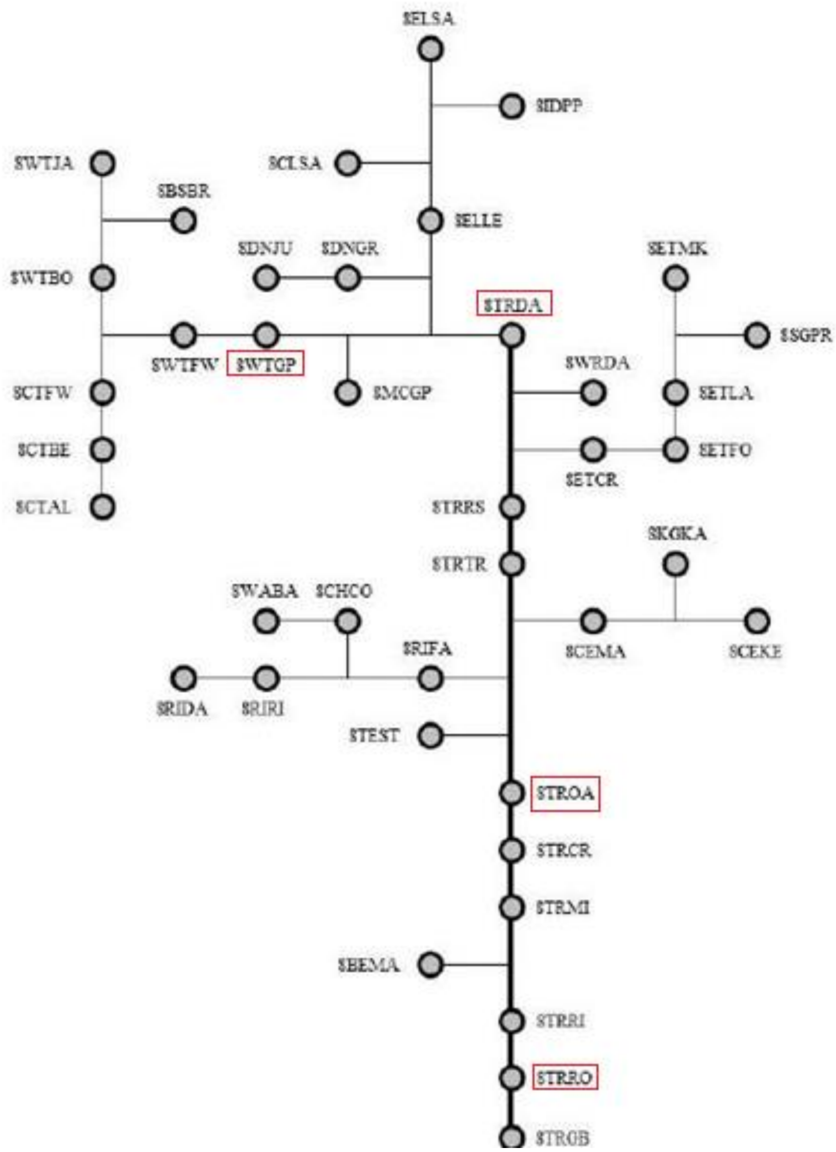

Figure 15 Schematic of Trinity System (Wurbs, 2017f)[7]

---

[7] Reprinted with permission *from Hydrology Update for the Trinity River Basin Water Availability Model*, by R. A. Wurbs, 2017, Texas Water Resources Institute, College Station, TX. Copyright 2017 by R. A. Wurbs.

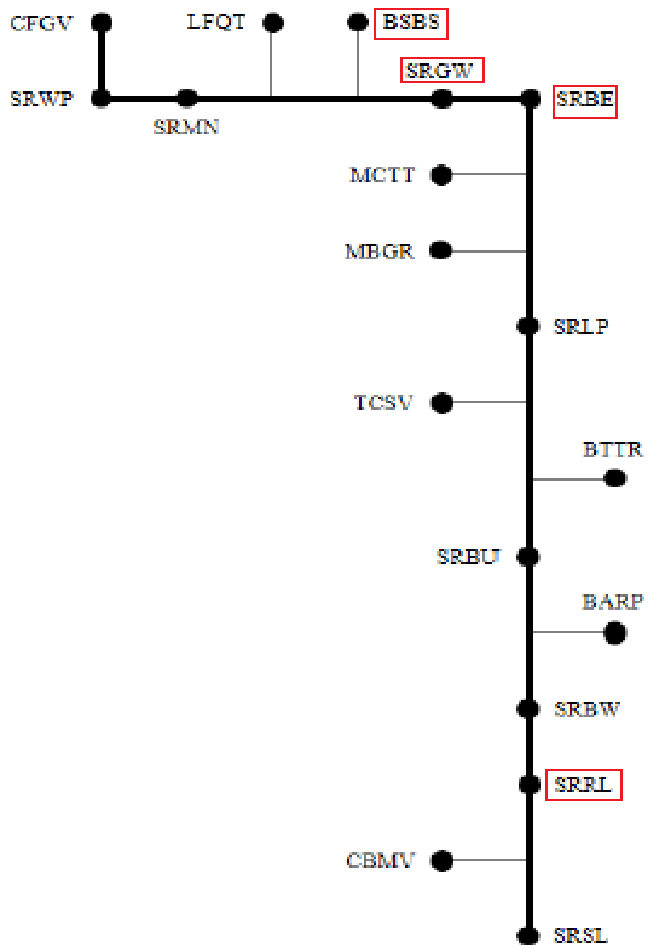

Figure 16 Schematic of Sabine System (Wurbs, 2017c)[8]

[8] Reprinted with permission from *Hydrology Update and Refinement for the Sabine River Basin Daily Water Availability Model*, by R. A. Wurbs, 2017, Texas Water Resources Institute, College Station, TX. Copyright 2017 by R. A. Wurbs.

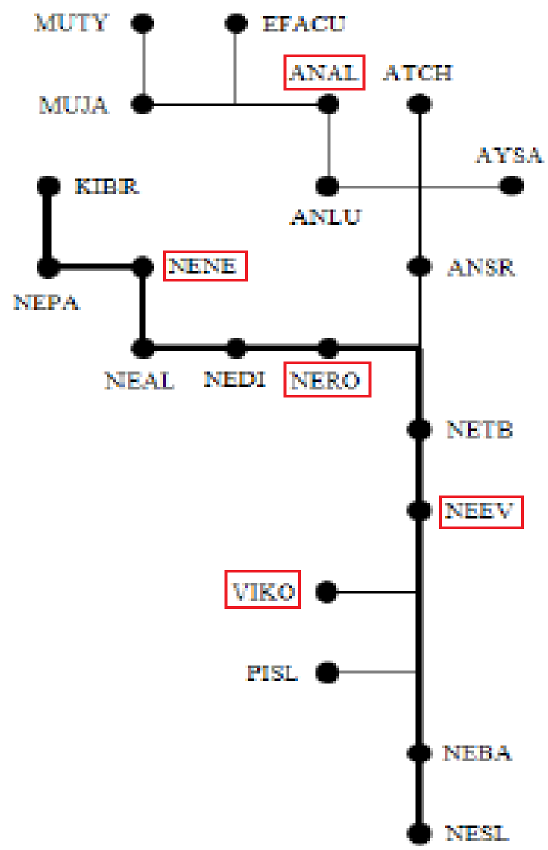

Figure 17 Schematic of Neches System (Wurbs, 2017b)[9]

[9] Reprinted with permission from *Hydrology Update and Refinement for the Neches River Basin Daily Water Availability Model*, by R. A. Wurbs, 2017, Texas Water Resources Institute, College Station, TX. Copyright 2017 by R. A. Wurbs.

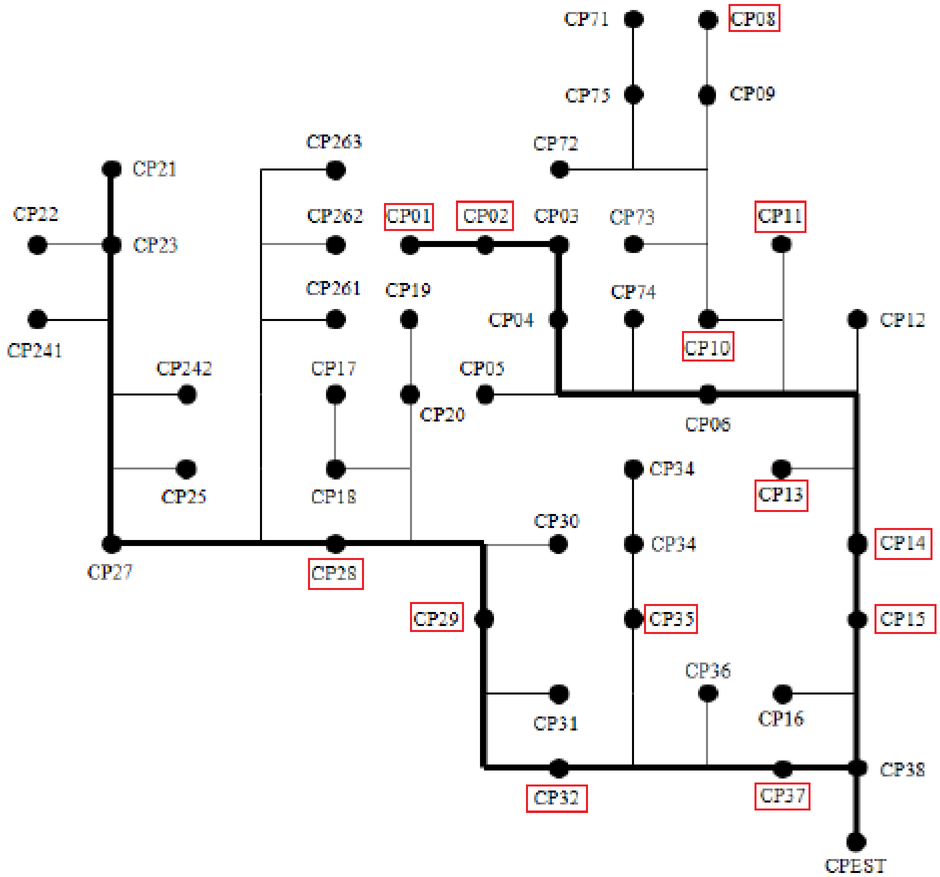

Figure 18 Schematic of GSA System (Wurbs, 2017a)[10]

[10] Reprinted with permission from *Hydrology Update and Refinement for the GSA River Basin Daily Water Availability Model*, by R. A. Wurbs, 2017, Texas Water Resources Institute, College Station, TX. Copyright 2017 by R. A. Wurbs.

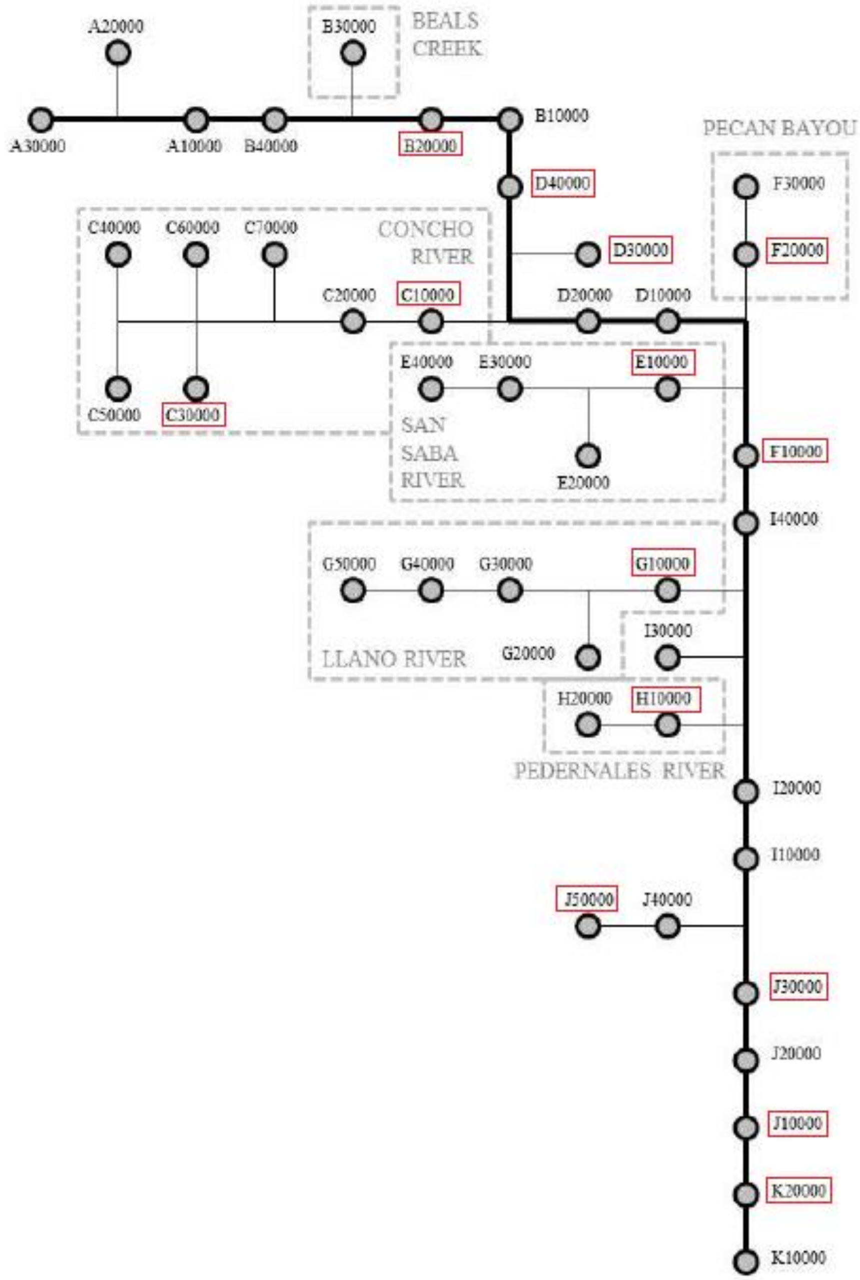

Figure 19 Schematic of Colorado System (Wurbs, 2017e)[11]

[11] Reprinted with permission from *Hydrology Update for the Colorado River Basin Water Availability Model*, by R. A. Wurbs, 2017, Texas Water Resources Institute, College Station, TX. Copyright 2017 by R. A. Wurbs.

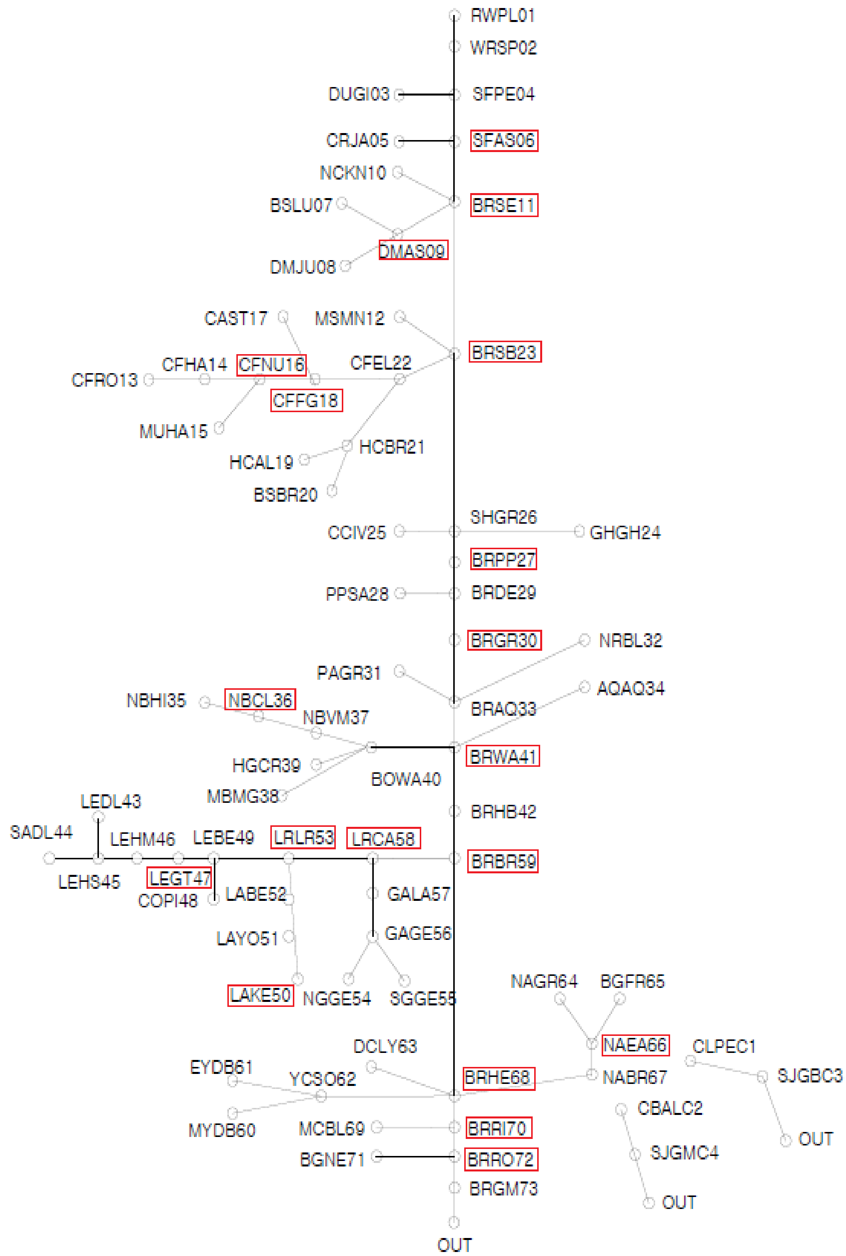

Figure 20 Schematic of Brazos System (Wurbs, 2017d)[12]

[12] Reprinted with permission from *Hydrology Update for the Brazos River Basin Water Availability Model*, by R. A. Wurbs, 2017, Texas Water Resources Institute, College Station, TX. Copyright 2017 by R. A. Wurbs.

7. SUMMARY AND CONCLUSIONS

The thesis research consists of two parts. The first part is the review presented in Section 2 of environmental instream flow standards implemented in Texas pursuant to the 2007 Senate Bill 3. The second part consists of WRAP/WAM simulation studies and the associated frequency analyses covered in Sections 3, 4, 5, and 6 that employ recently developed capabilities for incorporating SB3 environmental flow standards in water availability modeling. The simulation studies focus on analyzing the attainment of the SB3 environmental flow standards in six river systems and assessing the impacts of the environmental flow standards on unappropriated flows that are still available for future water right applicants. A strategy for incorporating complex daily modeling capabilities in the routinely applied monthly WAM system was also investigated.

The SB3 environmental flow standards at the seven river-bay systems, prioritized by the TCEQ, were defined following a similar approach. However, the complexity and general structure varies between systems. The key factors used to define the final environmental flow standards, such as the number of seasons, hydrologic conditions, and the number of control points change depending on not only the system, but also the gaging station that is being analyzed.

As presented in Section 2, several seasons can occur at the same time (e.g., December corresponds to fall in the Sabine-Neches system, while in some parts of the Colorado-Lavaca and Nueces systems, December is associated with winter). The influence of hydrologic conditions is relevant only in the Colorado, GSA, Brazos, and

Rio Grande systems, which increases the complexity of the SB3 standards defined in these systems. Similarly, there is great variation in the number of control points where SB3 environmental flows are defined (e.g., 4 in the Trinity system and 19 in the Brazos system) because of selection factors such as the size of the system and the information available regarding modifications that could have affected the hydrologic records.

Section 3 provides a description of the WAM/WRAP modeling system and the six daily WAMs for which the environmental flow standards have been developed. The attainment of the SB3 environmental flow standards in the six river systems is then assessed in Section 4 using the daily model capabilities. Frequency metrics for the monthly summations of daily instream flow shortage volumes and the daily instream flow shortage volumes at SB3 sites, as well as the mean instream flow targets are computed. These analyses reveal that both the frequency and magnitude of the instream flow shortages vary geographically within each system. The instream flow shortages can be as high as 97% percent of the mean shortage depending on the frequency, control point, and the system that is being analyzed.

The daily shortage volumes were also used to estimate the percentage of time with a non-zero shortage volume and it can be concluded that instream flow shortages occur at 40, 50, 40, 50, 90, and 50% of the time in the Trinity, Sabine, Neches, Colorado, GSA, and Brazos systems respectively. The maximum mean shortage occurs in the Brazos system and corresponds to the control point that has the greatest mean instream flow target. However, the maximum ratio (49%) of the mean instream flow shortage to the mean instream flow target computed individually for each control point occurs in the GSA system. If an average of these ratios is calculated to obtain a mean attainment of the instream flows in each system, then the Brazos system has the maximum ratio amongst all the systems.

Pulse flows were also analyzed comparing the total number of events that were completed to the theoretical total established by the SB3 environmental flow standards. Although the attainment of pulse flow events depends on the control point that is being evaluated, it is possible to compute an attainment level for the whole basin by adding all the completed and theoretical pulse events as presented in Section 4. From this analysis, it is concluded that the attainment levels are 69, 72, 62, 52, 56, and 71% in the Trinity, Sabine, Neches, Colorado, GSA, and Brazos systems, respectively.

The methodology proposed by Wurbs and Hoffpauir (2013) was implemented in three case studies (Trinity, Sabine, and Neches) in order to compare the attainment of SB3 environmental instream flow standards to the results obtained with the daily model. Frequency metrics for monthly instream flow shortage volumes were computed in the SB3 sites. The frequency and magnitude of the shortage volumes vary greatly as compared to the monthly summations of the daily shortages that were calculated with the daily model. The maximum shortages obtained with the monthly simulation are always greater than or equal to the values computed with the daily model. The frequency analysis revealed that the percentages of time with non-zero shortages are 50, 10, and 25% in the Trinity, Sabine, and Neches systems, respectively. These values are lower than the percentages obtained in the daily model.

The number of pulse flow events that are initiated, terminated, and completed cannot be tracked with the monthly model because the PF record is a capability that was recently developed for the daily model. This is a disadvantage of the monthly simulation approach as compared to the daily methodology considering that pulse flows are key elements of the SB3 environmental flow standards. Despite this shortcoming, the main advantage of the monthly model is that the amount of input records, complexity of the .DAT file, and computational time required to perform the simulations is considerably reduced compared to the daily model.

Frequency metrics for regulated flows were computed to compare the results obtained with the daily and monthly models. From this analysis, it is concluded that the maximum percentage differences of the mean regulated flows in the SB3 sites is 3, 1, and 10% for the Sabine, Neches, and Trinity systems. Additionally, the regulated flows computed with the daily model tend to be greater than or equal to the results obtained with the monthly model.

The SB3 environmental flow standards do not affect the water availability of the water rights currently included in the daily WAMs analyzed, because the effective priority date of the standards varies between the river systems from December 2009 to September 2012. Based on this, frequency analyses were developed for unappropriated flows in the SB3 EF sites. These analyses were done using a daily time step in simulations with and without including the SB3 environmental flow standards. As expected, water availability is reduced once the environmental flow standards are included. It is concluded from the analysis that the percentage of time with non-zero unappropriated flows ranges from 0.5% to 30% and 0.5% to 25% for the simulations with and without including SB3 environmental flow standards. The lowest percentages of time with water available for new water rights are 0.5, 2, and 2% in the GSA, Colorado, and Brazos systems. For this reason, acquiring new water rights in each basin has become a difficult task, considering that environmental flow standards are not fully attained; there are not enough unappropriated flows to cover the water demand. This statement is especially valid for the Colorado system. In the simulation that includes SB3 flow standards, for over 90% of the time unappropriated flows have been reduced to zero acre-feet/day.

From the frequency analyses, it can be seen that there is a spatial variation of unappropriated flows. The magnitude and frequency of unappropriated flows increase from upstream to downstream in all the river systems. This trend also occurs while analyzing SB3 environmental flow standards; the attainment levels increase from upstream to downstream in all the river systems.

REFERENCES

Acreman, M., & Dunbar, M. J. (2004). Defining Environmental River Flow Requirements. *Hydrology and Earth System Science, 8*(5), 861-876.

Gippel, C. J., Cosier, M., Markarc, S., & Liud, C. (2009). Balancing Environmental Flows Needs and Water Supply Reliability. *International Journal of Water Resources, 25*, 331-353.

Hoffpauir, R., Pauls, M., & Wurbs, R. (2013). *Application of Expanded WRAP Modeling Capabilities to the Colorado WAM.* College Station: Texas Water Resources Institute.

Hoffpauir, R., Pauls, M., & Wurbs, R. (2014). *Daily Water Availability Model for the Trinity River Basin.* College Station: Texas Water Resources Institute.

Hydrologics, Inc. (2009, December 1). *User Manual for OASIS with OCL.* Retrieved June 4, 2016, from http://www.hydrologics.net/documents/OASIS_Manual4-2010.pdf

Klipsch, J. D., & Hurst, M. B. (2013). *HEC-ResSim Reservoir System Simulation User's Manual.* Davis, CA: US Army Corps of Engineers.

Labadie, J. W. (2006). *MODSIM: Decision Support System for Integrated River Basin Management.* Fort Collins: Colorado State University, Department of Civil Engineering.

Mathews, R., & Richter, B. (2007, August 16). Application of the Indicators of hydrologic Alteration Software in Environmental Flow Setting. *Journal of the American Water Resources Association, 43*(6), 1400-1413.

National Research Council. (2005). *The Science of Instream Flow: A Review of the Texas Instream Flow Program.* Washington, DC: The National Academies Press.

Nature Conservancy. (2009). *Indicators of Hydrologic Alteration Version 7.1 User's Manual*. Retrieved June 8, 2016, from https://www.conservationgateway.org /Documents/IHAV7.pdf

O'Keefe, J., Raven, P. J., & Boon, P. J. (2012). Chapter 4: Environmental Flow Allocation as a Practical Aspect of IWRM. In *River Conservation and Management*. Hoboken, NJ: John Wiley & Sons.

Paredes-Arquiola, J., Martinez-Capel, F., Solera, A., & Aguilella, V. (2013). Implementing Environmental Flows in Complex Water Resources Systems—Case Study: The Duero River Basin, Spain. In *River Research and Applications* (pp. 451-468). Hoboken, NJ: John Wiley & Sons.

Pauls, M. A. (2014). *Incorporating and Evaluating Environmental Instream Flows in a Priority Order Based Surface Water Allocation Model.* Master of Science Thesis, Texas A&M University, Civil Engineering, College Station.

Pauls, P. A., & Wurbs, R. A. (2016, August). Environmental Flow Attainment Metrics for Water Allocation Modeling. *Journal of Water Resources Planning and Management*, *142*(8), 1-9.

Poff, L. N., & Zimmerman, J. K. (2009). Ecological Responses to Altered Flow Regimes: A Literature Review to Inform the Science and Management of Environmental Flows. *Freshwater Biology, 55*, 194-205.

Texas A&M and U.S. Bureau of Reclamation. (2007, July 18). *Hydrologic Modeling Inventory*. Retrieved June 8, 2016, from http://hydrologicmodels.tamu.edu /Adjusted_Apr_2010/Precipitation_runoff_models_49/Environmental_models_9/ WRIMS.pdf

University of Colorado at Boulder. (2016, May 11). *RiverWare: Overview*. Retrieved June 8, 2016, from Center for Advanced Decision Support for Water and Environmental Systems: https://cadswes.colorado.edu/creative-works/riverware

Wurbs, R. A. (2004, June). Water Allocation Systems in Texas. *International Journal of Water Resources Development, 20*(2), 229-242.

Wurbs, R. A. (2005, August). Texas Water Availability Modeling Systems. *Journal of Water Resources Planning and Management*, *131*(4).

Wurbs, R. A. (2011). Generalized Models of River System Development and Management. In U. Uhlig (Ed.), *Current Issues of Water Management* (pp. 1-22). Palm Beach, FL: InTech.

Wurbs, R. A. (2015a). *Water Rights Analysis Package Modeling System Reference Manual.* College Station: Texas Water Resources Institute.

Wurbs, R. A. (2015b). *Water Rights Analysis Package Modeling System Users Manual.* College Station: Texas Water Resources Institute.

Wurbs, R. A. (2017a). *Hydrology Update and Refinement for the GSA River Basin Daily Water Availability Model.* College Station: Texas Water Resources Institute.

Wurbs, R. A. (2017b). *Hydrology Update and Refinement for the Neches River Basin Daily Water Availability Model.* College Station: Texas Water Resources Institute.

Wurbs, R. A. (2017c). *Hydrology Update and Refinement for the Sabine River Basin Daily Water Availability Model.* College Station: Texas Water Resources Institute.

Wurbs, R. A. (2017d). *Hydrology Update for the Brazos River Basin Water Availability Model.* College Station: Texas Water Resources Institute.

Wurbs, R. A. (2017e). *Hydrology Update for the Colorado River Basin Water Availability Model.* College Station: Texas Water Resources Institute.

Wurbs, R. A. (2017f). *Hydrology Update for the Trinity River Basin Water Availability Model.* College Station: Texas Water Resources Institute.

Wurbs, R. A., & Hoffpauir, R. J. (2013). *Environmental Flows in Water Availability Modeling.* College Station: Texas Water Resources Institute.

Wurbs, R. A., & Hoffpauir, R. J. (2015). *Water Rights Analysis Package (WRAP) Daily Modeling System.* College Station: Texas Water Resources Institute.

Wurbs, R., Hoffpauir, R., Pauls, M., Ryu, M., & Bista, A. (2014a). *Daily Water Availability Model for the Neches River Basin.* College Station: Texas Water Resources Institute.

Wurbs, R., Hoffpauir, R., Pauls, M., Ryu, M., & Bista, A. (2014b). *Daily Water Availability Model for the Sabine River Basin.* College Station: Texas Water Resources Institute.

Wurbs, R., Hoffpauir, R., & Schnier, S. (2012). *Application of Expanded WRAP Modeling Capabilities to the Brazos WAM.* College Station: Texas Water Resources Institute.

Wurbs, R., Ryu, M., Pauls, M., & Hoffpauir, R. (2014). *Daily Water Availability Model for the Guadalupe and San Antonio River Basins.* College Station: Texas Water Resources Institute.